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Abstract: A network of data recording stations has been progressively deployed over recent years in the Tanana Flats to better understand the hydrology of the wetlands and the hydrologic impacts of airboat use. All stations monitor logger temperature, water–soil temperature profiles, and water levels. The logger temperatures at each station accurately represent local air temperatures. Winter conditions contribute significantly to fen temperature extremes the following summer, and conversely, the thermal storage in the fen in the summer is important to temperature conditions the following winter. The water level data provided overall ranges for each fen and indicated a typical annual cycle. Slow recession occurs during the cold late fall and winter months as a result of groundwater outflow, and spring melt is a time of recharge and general water level recovery. Water levels in May through October vary significantly between years, depending on rainfall. Hydrologic deficits that develop in dry years can be eliminated by 1–2 wet months. Conversely, several consecutive large rains can cause high fen water levels. Surface outflows diminish as water levels fall, and moderate levels are sustained by normal rainfall. Data from the station pair at Birch Island Well–Murphy Fen indicate a direct connection throughout the year between water beneath the permafrost and that in the nearby fens. Representative stations in each fen were selected to use for management of airboat access according to local water levels. Staff gauges that can be monitored by web cameras were installed at each of these stations in August 2007. The harsh environment, remote locations, and limited opportunities for access to the stations have often interrupted the continuity of data records. As a result, hydrologic issues remain to be resolved that will require continued station maintenance and operation.

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Preface

This report was prepared by Michael G. Ferrick, Charles H. Racine, and Charles M. Collins, Biogeochemical Sciences Branch, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center (ERDC), Hanover, NH; Stephanie P. Saari and Arthur B. Gelvin, Engineering Resources Branch, CRREL-ERDC; Steven Reidsma, U.S. Army Garrison Alaska, Fort Wainwright, Alaska; and Gary Larsen, U.S. Army Garrison Alaska, Fort Richardson, Alaska.

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The report was prepared under the general supervision of Dr. Terry Sobecki, Chief, Biogeochemical Sciences Branch; Dr. Lance Hansen, Deputy Director; and Dr. Robert E. Davis, Director, CRREL.

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1 Introduction

The Tanana Flats near Fairbanks in interior Alaska is part of the large lowland between the Alaska Range to the south and the Tanana River to the north. Flow through this vast fen complex is generally from the foothills in the southeast toward the river in the northwest. The shallow groundwater beneath these fens remains unfrozen year-round, but forests adjacent to and surrounded by the fens are situated on relatively warm, ice-rich permafrost that is sensitive to climate warming. With no gauged streams or water quality studies available, very few data exist to document the hydrology of the Tanana Flats. The low relief of the area contributes to complex drainage patterns and poorly defined outflow locations.

Airboats have become increasingly common in Alaska, and their use can potentially alter the hydrologic response of wetlands and affect ecosystem processes. This study assesses the hydrologic impacts of airboat trails through fen vegetation and airboat damage to access/egress points that together can induce changes in water flow and levels within the Tanana Flats wetland. The goal is to develop scientifically based management tools that minimize airboat impacts and sustain and conserve this valuable natural resource. This report focuses on the analysis of data obtained from a system of stations deployed in Tanana Flats. Related work on other hydrological aspects of the study is given by Ferrick et al. (2008), and airboat impacts to fen ecosystems and wildlife are discussed by Jorgenson et al. (2006a) and (2006b).

A network of data recording stations has been progressively deployed throughout the study area in the Tanana Flats (Fig. 1) in an effort to better understand the hydrology of the wetlands and to document any impacts that have resulted from the use of airboats. Multiple stations now exist in both the Upper Fen and Lower Fen that are trafficked by airboats, while a single station serves as a control near the outlet of the undisturbed Crooked Creek Fen. All stations monitor air temperature, water and soil temperature profiles, and water levels.

The Upper Fen stations include Birch Island Fen, Murphy Fen, Birch Island Well, and Upper Headwater/Upper Degraded Island. The relative locations of these stations are depicted in Figure 2. The Birch Island Fen

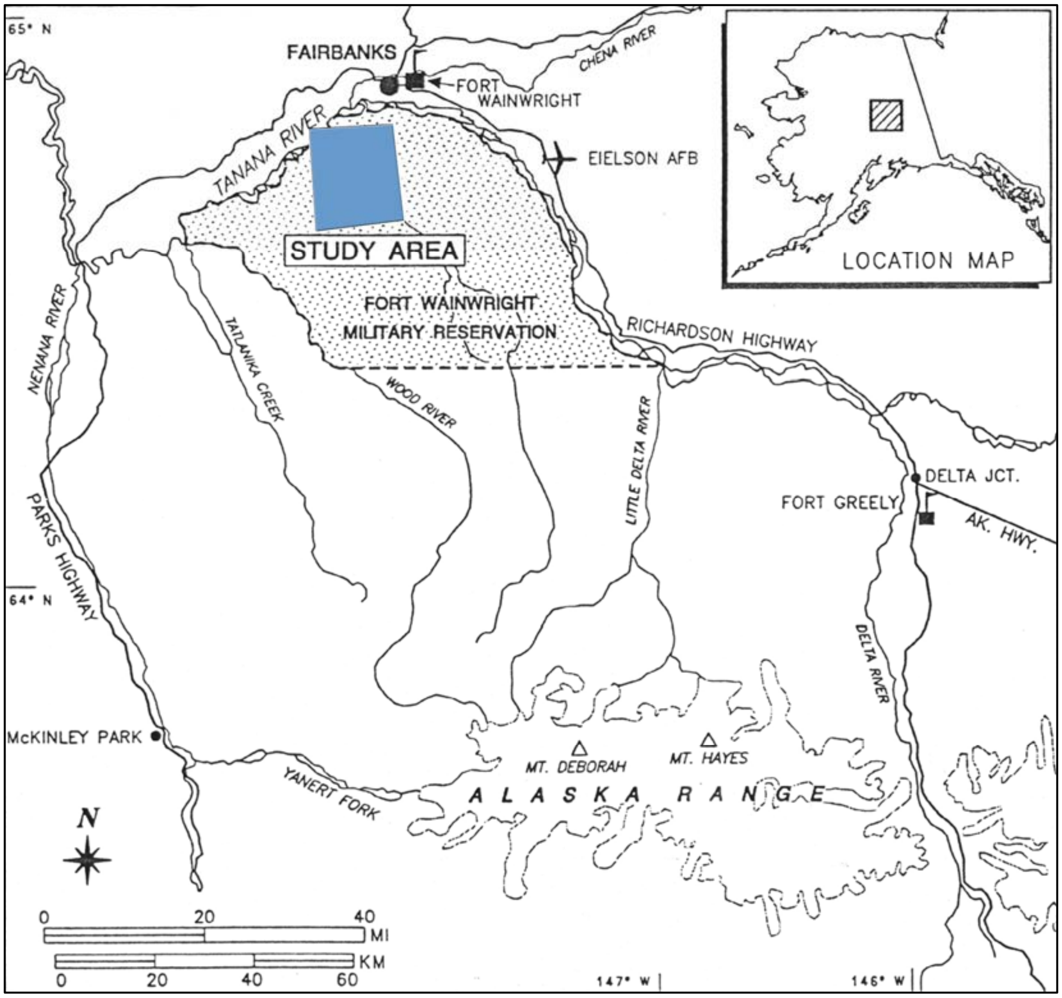

Figure 1. Location map showing the Tanana Flats portion of Fort Wainwright and the airboat use study area.

station, installed near Birch Island in March 1995, was the original fen monitoring station. The Murphy Fen station, located less than 1 km down-fen from the Birch Island Fen station, monitors rainfall and fen water conductivity in addition to temperatures and water level. The Birch Island Well station, located about 50 m from the Murphy Station, monitors both temperature and hydraulic head of the groundwater beneath the Birch Island permafrost, air temperature, and the near-surface temperature profile of the permafrost. The Upper Headwater station was located in a natural pond a few kilometers up-fen from the other stations. It was subsequently replaced by the Upper Degraded Island station, located about 1 km farther up the fen.

Lower Fen stations shown in Figure 2 include Lower Fen Headwater, Sunken Stream, and Willow Creek Fen. Lower Fen Headwater is located in

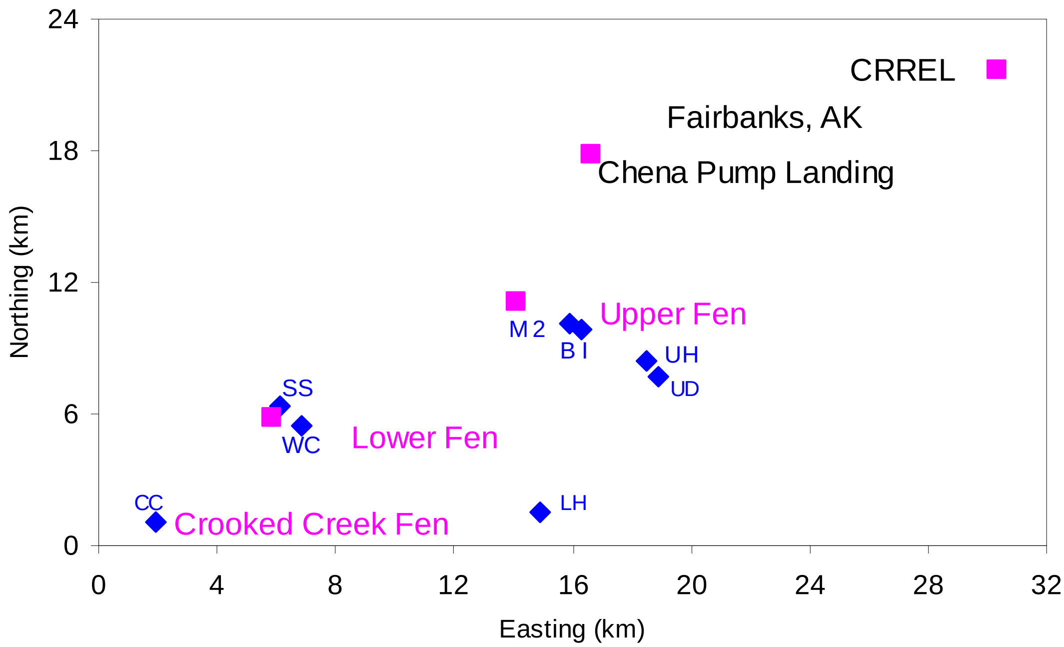

Figure 2. Relative monitoring station locations in the Tanana Flats near Fairbanks, Alaska: Upper Fen monitoring stations M2 = Murphy 2, BI = Birch Island Fen, UH = Upper Fen Headwater, and UD = Upper Degraded Island; Lower Fen monitoring stations SS = Sunken Stream, WC = Willow Creek fen, and LH = Lower Fen Headwater; and the untrafficked Crooked Creek Fen monitoring station CC. In addition, a station monitoring the well through the Birch Island permafrost is located within 50 m of the M2 site.

a headwater area of the Lower Fen. The Sunken Stream station is located on an outlet channel of the Lower Fen that leads to a slough of the Tanana River. The Willow Creek Fen station is located in a large fen area just above an outlet from the Lower Fen to Willow Creek. Though separated by less than 1 km, the Sunken Stream and Willow Creek stations are in different drainages. Finally, the Crooked Creek Fen station, located in an undisturbed fen less than 1 km from its outlet to Crooked Creek, serves as a control.

In this report we show that logger temperatures at each station accurately represent local air temperatures, and we describe the profile temperature and water level data obtained to date at each station, showing selected records. The discussion relating to a given station omits periods when the data record is missing. The available data are then analyzed by fen and overall to support conclusions relating to the hydrology of the wetlands and the management of airboat access. Finally, suggestions are given for continued productive use of this station network.

2 Logger Temperature–Air Temperature Comparison

The Tanana Flats station loggers deployed in the Upper Fen are in closest proximity to the Fairbanks Airport. Stations in the Lower Fen and the Crooked Creek Fen are several kilometers farther removed but are also relatively local to the airport. Logger temperatures, measured on a 4-hour interval at all stations, appear to provide accurate measures of local air temperature at the stations, including diurnal fluctuations. Table 1 compares the monthly average April through October logger temperatures between stations and with corresponding Fairbanks Airport monthly average air temperatures. Long-term monthly average temperatures at the airport are also given in Table 1 to provide a context for the study years.

Airport temperatures indicate that 2004 had the warmest and 2006 the coolest spring–summer–fall of these study years. The April through October periods of both 2004 and 2005 were warmer than average, while 2006 was slightly cooler than average. The monthly average Upper Fen logger temperatures were in good and consistent agreement with the airport temperatures in 2004, with the Murphy logger values higher by 0.3°C on average. In both 2005 and 2006 the Birch Island Well monthly average logger temperatures were within 0.1°C of the corresponding airport air temperatures. The Murphy logger temperatures in these years were consistently a fraction of a degree higher than those of both the nearby Birch Island Well and the Fairbanks Airport. The Sunken Stream logger temperatures at an outlet of the Lower Fen were consistently coolest of all the available station temperatures for each month in both 2005 and 2006. All the monthly average temperatures are in consistent agreement between the stations that provided data over the 3-year period. Temperature agreement between stations and with the airport supports the hypothesis that logger temperatures accurately represent local air temperatures.

Birch Island air temperatures varied through a range of 73°C over the monitored period. Mid-June through mid-August was the warmest period, with a peak temperature of 29°C in late June 2007. Air temperatures transition sharply from summer to winter during late September into November, with a minimum for the monitored period of –44°C in late

January 2006. Temperatures repeat the sharp transition in reverse, from winter to summer, during April and May.

Table 1. Average monthly temperatures (°C).

	April	May	June	July	August	September	October
1949–2006							
Fairbanks Airport	–0.4	9.3	15.6	16.7	13.6	7.2	–3.9
2004							
Fairbanks Airport	1.7	11.8	19.4	18.0	16.8	3.8	–1.3
Murphy	2.1	11.9	19.7	18.4	17.4	3.5	–0.6
Upper Headwater	2.2	11.6	19.7	18.4	—	—	—
2005							
Fairbanks Airport	0.1	13.1	16.4	16.8	14.1	7.9	–2.6
Murphy	1.2	13.7	—	—	—	8.3	—
Birch Island Well	0.7	13.5	16.4	16.5	13.4	7.3	–2.7
Willow Creek Fen	—	—	—	17.5	15.2	7.9	–2.0
Sunken Stream	–0.5	13.1	15.9	16.3	13.1	—	—
2006							
Fairbanks Airport	–1.4	10.1	14.9	16.4	—	—	—
Murphy	0.3	11.0	15.6	—	—	9.4	–0.3
Birch Island Well	–1.0	10.2	15.0	16.8	12.7(p)	—	—
Upper Fen Degraded Island	—	—	—	—	—	8.6	—
Lower Fen Headwater	1.3	12.1	16.8	17.4	11.8	8.5	–0.6
Willow Creek Fen	1.1	11.9	16.6	18.0	13.3	9.8	–0.3
Sunken Stream	–1.4	9.9	14.6	16.3	11.8	8.3	–1.1

(p) partial (incomplete) month

3 Upper Fen

Temperature Profile Measurements

Birch Island Fen

A vertical string of thermistors was installed to a depth of 3 m in the Upper Fen near Birch Island in March 1995 at nominal depths that correspond to low water conditions (0.1, 0.5, 1, 2, and 3 m). The temperature profile record at the station has been intermittent from that time until July 2005, when high fen water levels flooded the logger. This station was reinstalled in 2006 and provides by far the longest available record of fen temperatures for the Tanana Flats.

Large diurnal air, 0.1-m, and 0.5-m Birch Island Fen temperature fluctuations occurred throughout the summer of 1995. The 1-m temperature record also clearly indicates the influence of surface forcing with a response that is both averaged and lagged relative to shallower depths. Short-term influences from the surface remain visible at 2 m, but only a seasonal trend is in evidence at 3 m. Large diurnal air temperature fluctuations began in March 1996 and continued throughout the summer. Above-freezing temperatures occurred near the fen surface on several occasions in March, and significant thawing began in mid-April. Thaw at the 0.5-m depth on 28 April was immediately followed by diurnal temperature fluctuations at this depth. The thaw at 1 m on 11 May was followed by an abrupt temperature increase to 7.9°C by 14 May. With frozen conditions persisting at the 1-m depth, cold water associated with thawing near the surface in late April caused sequential temperature decreases at the 2-m and then 3-m depths. The 2-m temperatures recovered immediately to begin the seasonal increase before the end of the month. In contrast the 3-m temperatures remained near the annual minimum until slowly beginning the seasonal increase in late May. A brief warming in mid-August is reflected with increasing lag in the profile temperatures at both the 1-m and 2-m depths.

The air and 0.1-m temperatures exhibited strong diurnal fluctuations from mid-March through mid-August 1997. The seasonal thaw in 1997 began on about 23 April. Thaw at 0.5 m was complete on 30 April and was followed immediately by strong diurnal temperature fluctuations in early May that

continued through the summer. Thaw at 1 m concluded on 9 May, but temperatures there remained less than 1°C until 16 May, when an abrupt increase to 10.2°C occurred, probably caused by mixing due to a significant flow event in the fen. A small temperature decrease at 2 m on 27 April was again followed immediately by the start of the seasonal temperature increase. However, this cooling event was not evident at the 3-m depth, where the gradual seasonal temperature increase began on 22 May.

Fen profile temperature data for 1998 extend from late March until late August. The seasonal thaw began early, on about 12 April. At the 0.5-m depth the thaw period extended from 17 to 27 April and was followed immediately by diurnal temperature variations on 28 April that rapidly increased in amplitude. Thaw at the 1-m depth on 13 May was followed by a gradual temperature increase to 3.0°C on 22 May and then, as in previous years, an abrupt increase to 7.1°C on 23 May. The profile temperature decrease at 2 m, from 1.0°C to 0.7°C on 12 April, occurred earlier in the season than for previous years. The 2-m temperatures then began a slow increase over six weeks to 1.6°C on 1 June, before starting a more rapid seasonal increase to a mid-August annual peak. The seasonal temperature increase at 3 m was also late relative to previous years, beginning on 15 June and attaining only 4.0°C by the end of the record on 23 August. It also included a seven-week plateau, from 2 May until 22 June, when temperatures varied by less than 0.1°C.

By December 1998 the freezing front had progressed about 1 m from the surface, the 0.5-m temperature was negative and moderately variable, and the 0.1-m and air temperatures were significantly lower and more variable. The data indicate probable exposure to the air of the 0.1-m thermistor throughout the winter. Temperatures at 2 m and 3 m were positive and nearly constant in December. Between 1 January and 15 March 1999 the air and 0.1-m temperatures were generally below –10°C. The freezing front clearly moved past the 1-m sensor by mid-January, and freezing temperatures approached but did not reach the 2-m sensor by the end of winter. Strong warming occurred at the station during March, with positive air temperatures toward the end of the month. By mid-April, air temperatures were largely positive, initiating the seasonal thaw at the surface on about 17 April. The winter temperatures at 0.5 m were lower than those at greater depth until mid-April, when a reversal occurred in response to warming at the surface. Spring thaw from 20 to 23 April at 0.5 m was followed by rapidly increasing temperatures and diurnal fluctuations. The

fen remained frozen at the 1-m depth, but the temperature there increased progressively from −2.2°C on 1 April to −0.2°C on 3 May. The deep thermistors at 2 m and 3 m cooled through the winter, reaching 0.3°C and 2.1°C, respectively, by early May. Even with the fen remaining frozen at 1 m, cold water from near-surface melt again migrated to the 2-m depth, decreasing the temperature there on 2–3 May by more than 0.1°C. This anomaly was the only deviation at 2 or 3 m from otherwise smooth seasonal temperature decreases into early May. The 3-m data indicate an annual temperature variation of the shallow groundwater that exceeds 3°C.

The fen temperature profile data for 2001 spans the months of July through September. Air temperatures in July were lower, and diurnal fluctuations were smaller in 2001 than for all other monitored years. For the first time, diurnal temperature fluctuations at 0.1 m were small throughout the summer, probably indicating greater submersion than normal. Smoothing and lagging from the 0.5-m record is evident in the 1-m record, and only smooth seasonal trends occurred at 2 and 3 m. Fairbanks Airport temperatures indicate that in 2001, May was 2.4°C below normal, June was 0.6°C above normal, July was 1.2°C below normal, August was 0.4°C above normal, and September was 1.4°C above normal. These data do not fully explain the observed fen temperature trends.

Fen temperature profile data for May through August 2002 indicate that air and 0.1-m temperatures increased rapidly in May, peaked in early June, were relatively cool and stable through late July, and then displayed a cooling trend through August. Water temperatures at and below 1-m depth were positive in mid-May, while shallower depths remained near or below 0°C. After complete thaw at 0.5 m on 24 May, the temperature there increased slowly to 0.7°C by 1 June, increased abruptly to 17.8°C on 5 June, and then remained relatively stable until mid-August, when the seasonal decrease began. In contrast, temperature at 1 m increased gradually from 2.7°C on 16 May to 15°C on 9 August, equal to the temperature at 0.5 m. The water temperatures at depths less than 1 m and the air temperature were nearly equal by the end of July, and well-mixed conditions at these depths then persisted through August. Temperatures at 2 and 3 m displayed seasonal trends through the monitored period without short-term fluctuations. At 2 m the temperature increased from 1.3°C on 16 May to an annual peak of 7.4°C on 16 August. Temperatures at 3 m increased progressively from 2.0°C on 16 May to 5.3°C on 28 August, not yet attaining an annual peak.

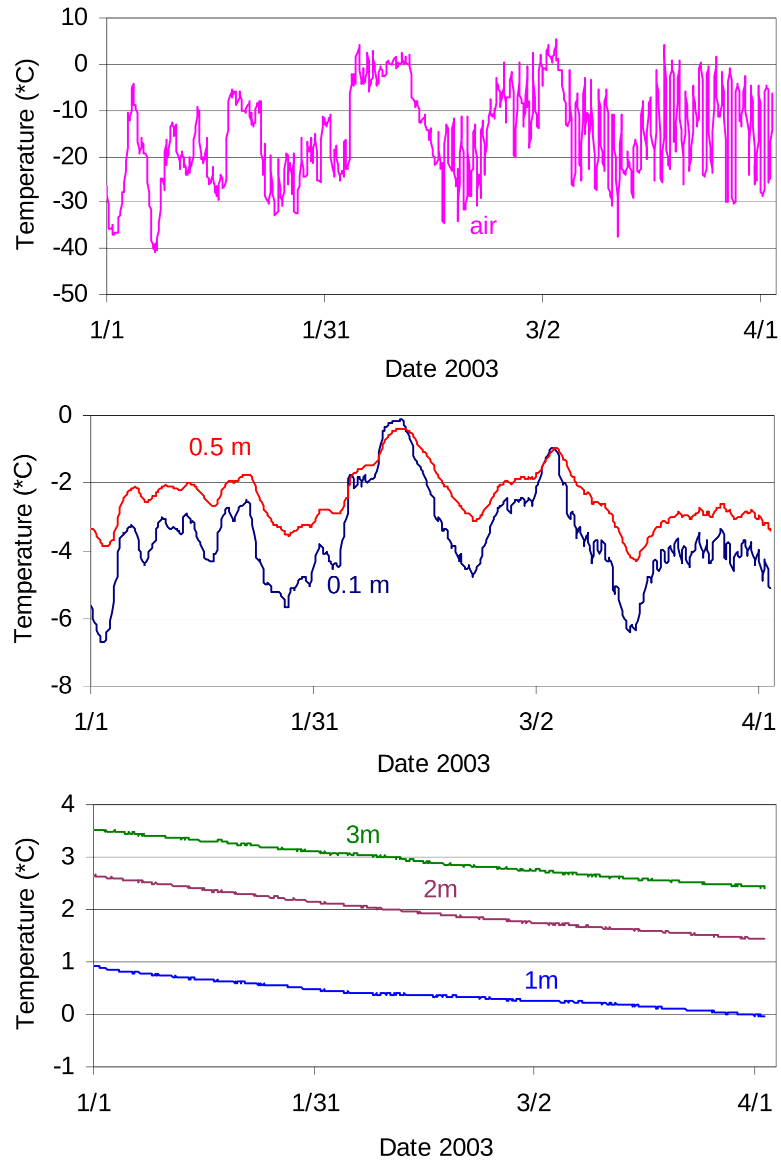

Figure 3. Air and fen profile temperatures at the Birch Island Fen station, January–March 2003.

Figures 3, 4, 5, and 6 provide fen profile temperatures for January–March, April–June, July–September, and October–December 2003, respectively. Subfreezing air temperatures persisted through most of January–March, with large and regular diurnal fluctuations beginning in mid-February. The temperatures at 0.1 and 0.5 m responded to the short-term trends through this period, and both remained subfreezing. At 1, 2, and 3 m the temperatures each displayed seasonal cooling trends with no indication of short-term influences. The 1-m temperature decreased to the freezing point by the end of March, while deeper temperatures remained above freezing. A strong warming trend in the air and 0.1-m temperatures

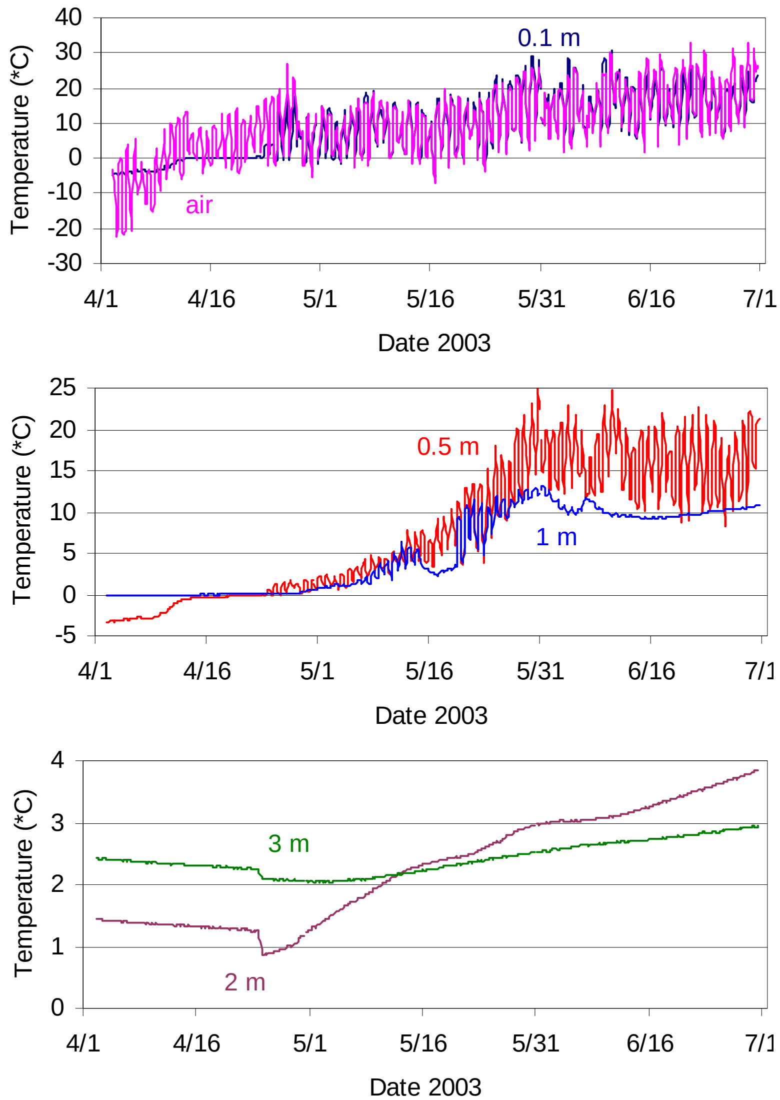

Figure 4. Air and fen profile temperatures at the Birch Island Fen station, April–June 2003.

occurred during April, followed by more gradual warming through June. Melt at 0.1 m was complete on 25 April, and diurnal temperature fluctuations at that depth began shortly afterward. Following thaw at 0.5 m on 23 April, both the temperatures and the diurnal fluctuations there increased progressively through May. Thaw at 1 m occurred earlier, on 16 April, but with melt occurring nearby, the temperature there remained below 0.2°C until 29 April. The temperatures at 1 m increased more slowly during May than those at 0.5 m, and these depths were generally stratified during June. As in previous years, the slowly decreasing temperature at 2 m changed to an abrupt decrease from 1.2°C to 0.9°C on 24 April, and the 3-m temperature also decreased from 2.2°C to 2.1°C. The 2-m temperature began the seasonal increase immediately after this decrease, while the 3-m

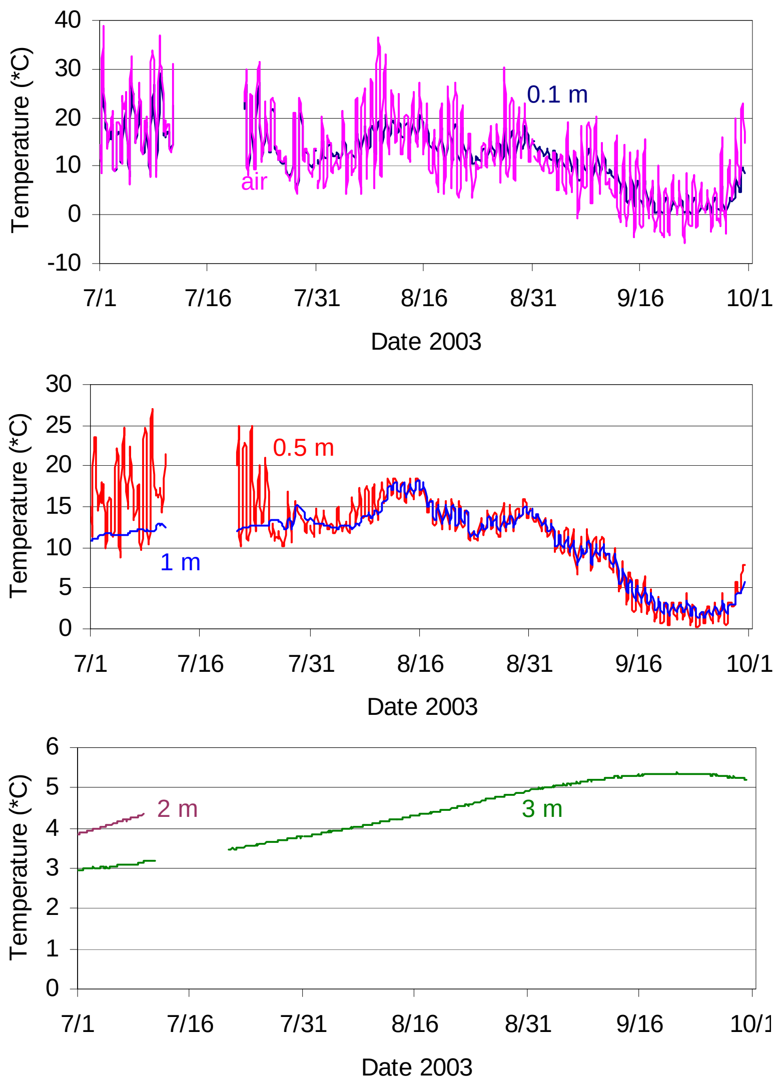

Figure 5. Air and fen profile temperatures at the Birch Island Fen station, July–September 2003.

temperature remained constant before starting its seasonal increase in mid-May. The temperature at 0.1 m closely tracked the air temperature during the summer months but displayed much smaller diurnal fluctuations. Relatively large diurnal fluctuations at 0.5 m and stratification with the 1-m depth ended in late July. Well-mixed conditions with a common and steady temperature at both depths persisted through August before these temperatures decreased sharply in September. The data at 2 m ended on 9 July, prior to the annual peak. At 3 m the temperature increased smoothly through the summer to an annual peak of 5.4°C on 19 September. Air and 0.1-m temperatures decreased together in the fall, finally separating in mid-November. Freezing occurred at 0.1 m on 16 October. Similarly, temperatures at 0.5 and 1 m started to decrease

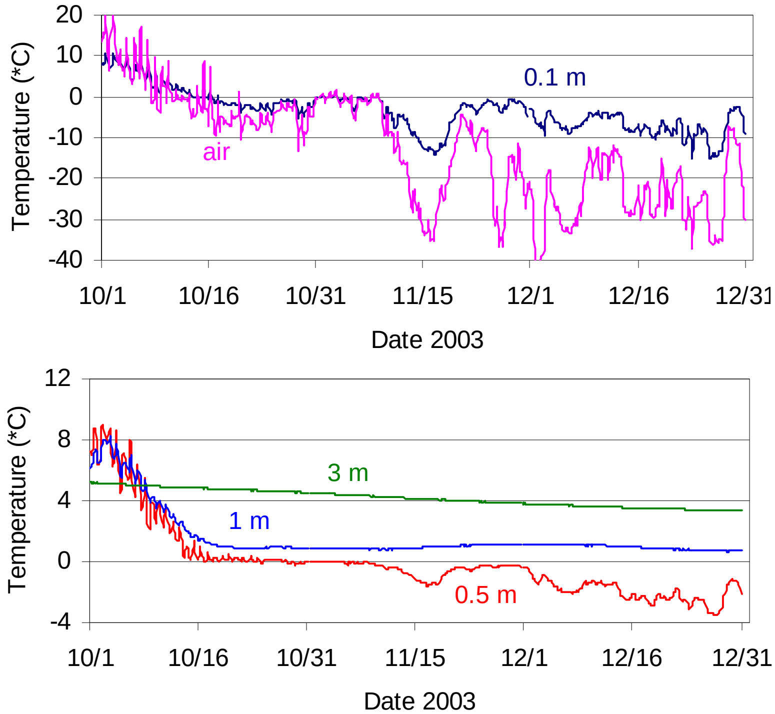

Figure 6. Air and fen profile temperatures at the Birch Island Fen station, October–December 2003.

together but separated by mid-October. The freezing period at 0.5 m was extended, lasting from 29 October until 10 November. With freezing occurring in the water column above, the rate of cooling at 1 m slowed significantly in late October, and this depth remained unfrozen through the end of the year. The 3-m temperature decreased linearly through the fall but remained well above freezing.

Frozen conditions progressed to just beyond the 1-m depth in 2004. The 1-m temperature decreased to the freezing point on 25 February, and most of the water there was frozen by 7 March at a seasonal minimum temperature of only –0.4°C. The air temperatures indicated the beginning of seasonal thaw in early April, and at 0.1 m the thaw was extended in time from 6 to 26 April. Temperatures at 0.5 m increased to near the freezing point on 10 April, but thaw did not progress until 30 April and was complete by 5 May. Frozen conditions at 1 m existed for only one month, as thaw began on 9 April and was complete by 15 April. The earlier thaw at 1 m than at shallower depths indicates probable heating from below. The linear temperature decrease at 3 m that began in the fall of 2003 continued through April 2004, reaching an annual minimum of 2.1°C on 2 May. Large air and 0.1-m temperature increases occurred during May, and the high temperatures attained continued through late August. The temperatures at 0.5 and

1 m increased more slowly than nearer the surface, peaking in late June with sustained high temperatures into late August. Temperatures at 3 m increased smoothly through this period, with no influence of short-term fluctuations at the surface. Air and 0.1-m temperatures gradually cooled through September and October. Subfreezing air temperatures that began in late October caused a freeze at 0.1 m over the period 22–28 October. The temperatures at 0.5 and 1 m cooled together in September to the freezing point before recovering in October. The freeze at 0.5 m extended from 7 to 23 November, while stable above-freezing temperatures persisted through December at the 1-m depth. The annual peak temperature of 6.6°C at 3 m was attained from 6 to 15 September. The 3-m temperature then decreased smoothly through December with no short-term influences.

Air temperatures in 2005 remained subfreezing until early March and indicate the start of seasonal thaw on 20 April. The seasonal minimum temperature at the 0.1-m depth, –14.9°C, occurred on 2 February, and the seasonal thaw at this depth spanned 20–27 April. At the 0.5-m depth the minimum temperature of –8.0°C occurred on 3 February, with seasonal thaw from 23 to 27 April. Temperatures at both the 0.1- and 0.5-m depths displayed short-term fluctuations driven by conditions at the surface. The freeze at the 1-m depth began on 11 March, attaining a minimum temperature of –0.2°C that was sustained from 2 to 24 April. Warming at this depth then followed immediately, with complete thaw by 29 April. Temperatures at the 3-m depth cooled linearly from 3.8°C at the start of January to 2.4°C by the end of April. The air and 0.1-m temperatures increased rapidly during May, and mild temperatures at the surface were sustained through the end of the record on 9 July 2005. The 0.5- and 1-m temperatures also increased rapidly in May, with diurnal and short-term fluctuations in evidence throughout the period. Stratification of the upper 1 m developed by the start of June and continued through the end of the record. The annual minimum temperature at the 3-m depth of 2.4°C occurred from 30 April until 7 May and was followed by a slow and then more rapid temperature increase without short-term fluctuations to 6.0°C in early July.

Murphy Fen

The original Upper Fen Murphy station was established on 11 July 2003, operating only until 24 August 2003, when it was destroyed. Logger temperature, representing that of the air, was variable between 2°C and 33°C in July–August. Diurnal heating and cooling superposed on alternating

warm and cool periods accounted for this large temperature variability. Thermal stratification of the upper 0.5 m of depth persisted through much of July, but well-mixed conditions through this depth began on 26 July and continued for the rest of the period. The 0.25- and 0.5-m temperatures generally increased from the start of the period to annual peaks over 15°C in mid-August. The temperature increase at 1 m began in late July, reaching an annual peak of 6.2°C on 18 August. Temperatures at 2 and 3 m increased monotonically from near 0°C in late July to 1.8°C and 0.9°C, respectively, near the end of August. Neither of these depths attained an annual peak temperature.

The Murphy station was reestablished on 25 March 2004 at a nearby, but more discreet, location near Birch Island (Fig. 7). Over time additional instruments have been added to this station, making it the most comprehensive site in the network. This instrumentation includes a tipping bucket rain gauge and sonic sounder for water level and snow depth measurements (Fig. 8), a water conductivity probe, and a staff gauge for daily May–September water level measurement and posting with web camera photographs (Fig. 9).

Figure 7. Installation of the new station at Murphy, March 2004.

Figure 8. Tipping bucket rain gauge (left) and sonic sounder (right) at Murphy station, August 2007.

Figure 9. Staff gauge at Murphy station for daily (May–September) water level measurement and posting with a web camera.

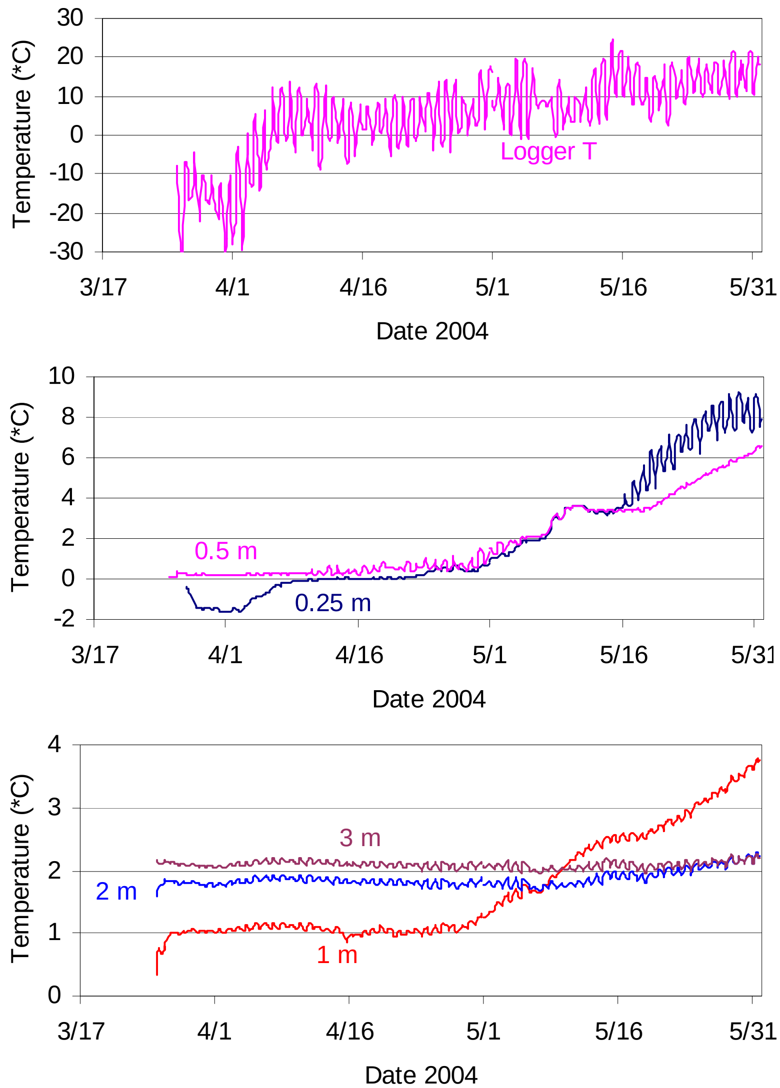

Figure 10. Logger and fen profile temperatures at the Murphy station, March–May 2004.

Logger and profile temperatures from the new station for March–May, June–August, and September–December 2004 are presented in Figures 10, 11, and 12, respectively. Air temperatures increased rapidly in early April to mostly above freezing later in the month, and May temperatures reflect continued gradual warming. The 0.25-m temperatures remained below freezing until late April, while temperatures at and below 0.5 m were all above freezing in late March. With persistent warm weather in May the 0.25- and 0.5-m temperatures increased rapidly toward respective highs of 9°C and 6.6°C near the end of the month. The 1-m temperature increased monotonically in May from 1°C to 3.8°C, the 2-m temperature increased from 1.8°C to 2.2°C, and the 3-m temperature remained constant between 2.1°C and 2.2°C. Logger temperature oscillated about

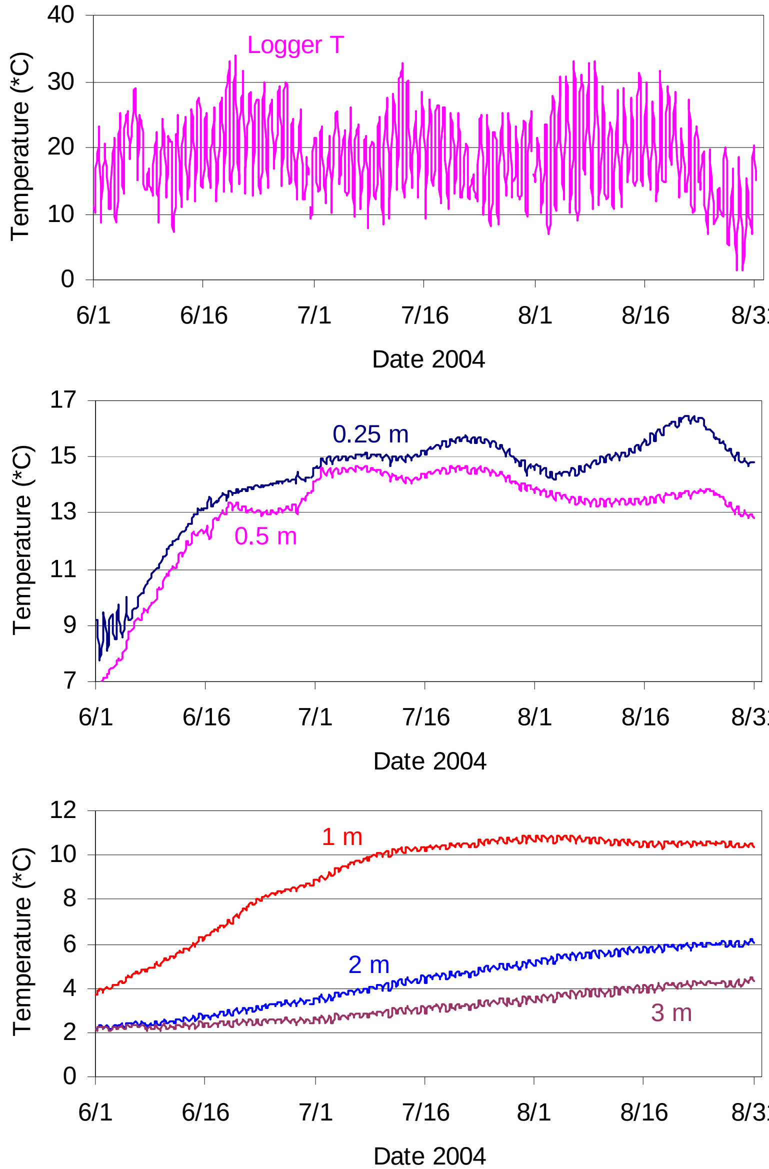

Figure 11. Logger and fen profile temperatures at the Murphy station, June–August 2004.

20°C over most of June–August until decreasing in late August. Temperatures at 0.25 m increased rapidly during June, approached 16°C in late July, and reached an annual peak above 16°C on 23 August. At 0.5 m the temperature also increased rapidly through June to a broad annual peak in July that exceeded 14°C for much of the month. The 1-m temperature increased through June–July to a broad peak of 10.8°C in early August. The temperatures at 2 and 3 m also increased throughout this summer period to above 6°C and 4°C, respectively. Diurnal fluctuations of the air temperature decreased into the fall and were small after mid-October, when temperatures remained below freezing. In response, the 0.25- and

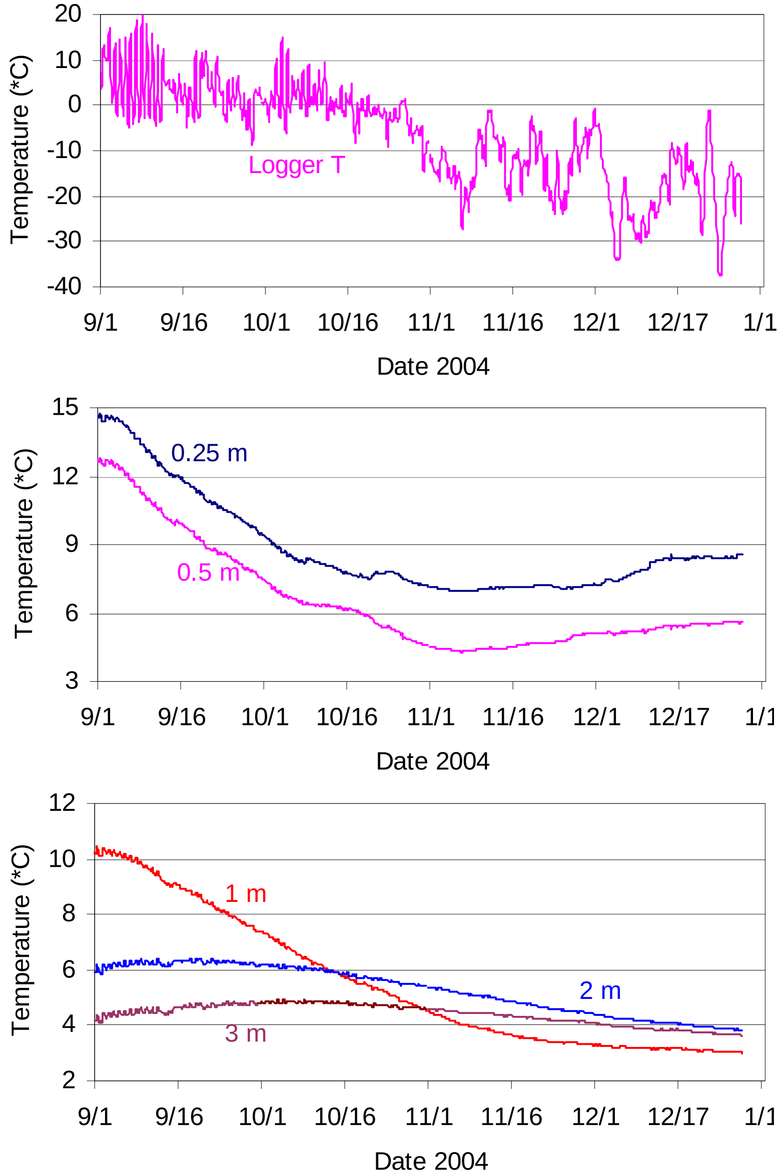

Figure 12. Logger and fen profile temperatures at the Murphy station, September–December 2004.

0.5-m temperatures decreased rapidly until 10 October, when their trajectories changed. Subsequent data at these depths are inconsistent with significantly lower air temperatures later in the fall. The temperature at 1 m decreased monotonically from early September through the end of the year, falling below that at 2 m on 15 October and below that at 3 m on 31 October, and eventually reaching 3.0°C. At 2 m the temperature displayed a broad annual peak during September, with a maximum of 6.4°C on the 19th. Temperature at 3 m also had a very broad annual peak, reaching a maximum of 4.9°C on several days between 4 and 12 October. The 2-

and 3-m temperatures converged toward the end of 2004 to 3.8°C and 3.6°C, respectively.

The working profile temperature sensors at Murphy resumed operation in mid-February 2005. In the interim, the temperatures at 1, 2, and 3 m all continued to decrease, with the 2-m temperature falling below that at 3 m. Logger temperatures reflect mild weather in mid-March and melt conditions after 6 April. Above-freezing low temperatures began on 20 April as part of a strong warming trend. The temperature decrease at 1 m continued to a minimum of 2.2°C on 30 March, followed by a slow increase to 2.4°C near the end of April. The temperature decreases at 2 and 3 m continued through the end of April, with minimums of 2.8°C and 3.1°C, respectively. Following the warming of late April through early May, the mean air temperature remained relatively constant into June, with large diurnal fluctuations. Station maintenance and instrument replacement was performed during site visits in late August 2005. As in prior years, air temperature diminished gradually in September and more rapidly from late October into November. The temperature at 0.5 m responded quickly to conditions at the surface, decreasing from 10.8°C on 1 September to 3.0°C on 4 November. The 1-m temperature also responded, going from an annual peak of 12.4°C on 24 August to 8°C on 4 November. The annual peak temperature at 2 m was 8.1°C on 21–23 October. At 3 m the annual peak of 6.3°C was very broad, spanning 21–31 October. The 2005 annual peak temperatures at 1, 2, and 3 m were each higher than those in 2004 by 1.6°C, 1.7°C, and 1.4°C, respectively.

The logger temperature data indicate a continuous warming trend during March through May 2006, with the usual snowmelt period in the latter half of April. A warm June and July followed, with cooler conditions in late August and most of September and below-freezing temperatures and reduced diurnal fluctuations beginning in mid-October. Profile temperatures were not available in 2006 until the sensors were replaced in August. Afterward, the temperatures at 0.25 m closely resemble the logger temperatures, except that several diurnal peaks are higher, indicating that this thermistor was above the water surface during this period. The 0.5-m temperatures were very similar to those of the logger and 0.25 m, except that amplitudes are greatly reduced. Water near this thermistor began to freeze on 23 October. The 0.75- and 1-m temperatures were close replicates of each other through August and September, including simultaneous annual peaks over 9.2°C on 20 September. After separation of these

temperatures on 9 October, the 0.75-m temperatures became subfreezing on 13 November and the 1-m temperatures reached freezing at the end of the year. The 1.5-, 2-, and 3-m temperatures had successively lower, broader, and later annual peaks of 6.1°C, 4.1°C, and 3.1°C on 23 September, 2 October, and 21 October, respectively. The annual peak temperatures at 1, 2, and 3 m were lower in 2006 than in either 2004 or 2005. Large peak temperature decreases of between 3.2°C and 4.0°C occurred at each of these depths in one year. The temperatures recorded over just three years of monitoring indicate that large and rapid changes in the thermal state of the Upper Fen are common.

Logger temperatures remained subfreezing from the start of 2007 until the end of March. The shallow profile temperatures followed those of the logger but were progressively higher, with smaller fluctuations as depth increased. Minimum temperatures reached –36°C on 9 January at 0.25 m, –9.7°C on 25 February at 0.5 m, –4.9°C on 26 February at 0.75 m, and –2.0 on 7 March at 1 m. Gradual cooling occurred during January–March at 1.5–3 m, with all these temperatures remaining above freezing. The logger, 0.25-, and 0.5-m temperatures increased together through April and indicate the start of melt early in the month. Large diurnal fluctuations and high temperatures show that the 0.25- and 0.5-m thermistors were out of the water from mid-April through July, while the 0.75-m thermistor remained submerged but very shallow. The logger temperature indicated a maximum air temperature of 31.2°C on 20 June, while the maximum temperatures at 0.25 and 0.5 m reached 38.0°C and 36.2°C, respectively, on 19 June. Thaw at 0.75 m was complete by 30 April, and a maximum temperature of 29.1°C was attained there on 22 July. The complete thaw on 19 May at 1 m was followed by a progressive temperature increase to 12.8°C on 1 August. Subfreezing temperatures at the 1.5-m thermistor persisted from mid-April through 14 July, followed by a relatively rapid temperature increase to 4.1°C by 1 August. The common abrupt seasonal temperature decreases at 2 and 3 m of 0.35°C and 0.13°C, respectively, occurred on 17 April. The 2-m temperature was then almost constant at 0.5°C until 10 July, increasing to 1.6°C by 1 August, while the 3-m temperature remained almost constant at 1.3°C through 1 August. These data indicate that fen surface temperatures at Murphy were highly stratified in summer 2007.

Upper Fen Headwater–Upper Degraded Island

The Upper Fen Headwater monitoring station was established on 5 April 2003 in a pond near the head of the primary fen of the Upper Fen system (Fig. 13). This station operated until it was removed by vandals in 2006. The Upper Degraded Island station was established as a replacement at a nearby, but more discreet, site on 23 August 2006 (Fig. 14).

Figure 13. Upper Fen Headwater station, March 2004.

Above-freezing local air temperatures at the Headwater station occurred through much of April and into May 2003. Ice melt on the surface of the pond was complete by early May, when temperatures at 0.25, 0.5, and 1 m rapidly increased above 0°C. Meanwhile, temperatures at the 2- and 3-m thermistors in the unfrozen sediment beneath the bottom of the pond were stable into mid-May at annual minimums between 0°C and 1°C. Similar to other stations the minimum temperature at 3 m was higher than that at 2 m. A warming trend at the end of September 2003 was followed by a gradual cooling, and by mid-October air temperatures were continuously below

Figure 14. Upper Degraded Island station installation, August 2006.

freezing. Pond 0.25- and 0.5-m temperature trends followed that of the air, increasing to an early October peak and then decreasing. The 0.25-m probe was incorporated in the ice cover by late October. The 1-m temperature near the bottom of the pond also responded to the air temperatures, decreasing to 2°C by the end of October. The 2- and 3-m temperatures recorded annual maxima in early October of 3.5°C and 2.9°C, respectively, but both temperatures began to decrease by the end of the month.

Logger and profile temperature data for 2004 from the Headwater station are presented in Figure 15. Air temperatures increased significantly in early April, followed by sustained warmth through the end of May. The thermistor at 0.25 m indicated thaw on 6 April, followed by a slow temperature increase to about 2°C at the end of the month and then a rapid increase during May to 13.7°C. The thermistor at 0.5 m indicated a frozen condition until the end of April, followed by a large temperature increase to 10.4°C at the end of May. The 1-m thermistor showed a mid-April thaw followed by a progressive temperature increase to 4.4°C in May. Annual temperature minimums between 0°C and 1°C were again recorded in early May at the 2- and 3-m depths. The minimum temperature at 2 m was less than that at 3 m, but warming during May equalized these temperatures by the end of the month. A warm June, cool start to July, and warm middle of July are reflected in the 0.25- and 0.5-m pond temperatures. The 1-, 2-, and 3-m temperatures all increased through the

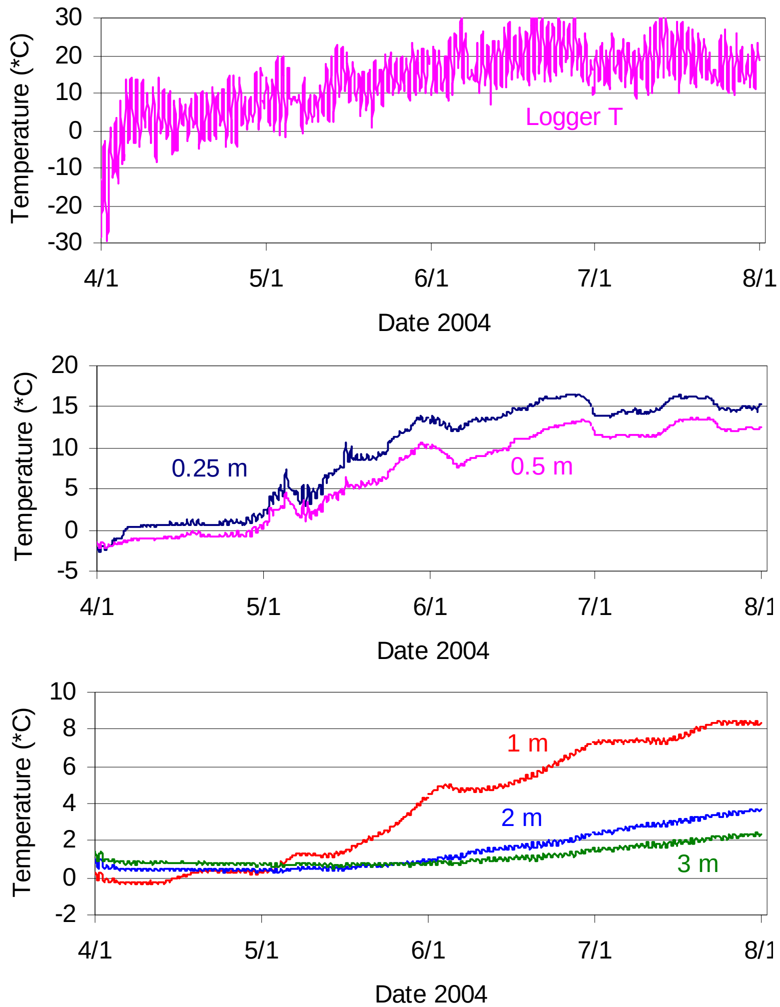

Figure 15. Logger and fen profile temperatures at the Upper Fen Headwater station, April–July 2004.

summer, but only the 1-m temperatures reflected the influence of short-term warm and cool periods. The pond was stably stratified throughout the summer. During June the pond temperatures increased least at 0.25 m and most at 1 m. There was no net change in the 0.25- and 0.5-m temperatures in July, but 1-m temperatures continued to increase. The rate of temperature increase during the summer decreased with depth for the deeper sensors. Early August temperatures of 3.8°C at 2 m and 2.4°C at 3 m were approaching seasonal maximums. Data were not recorded for any sensor outside the logger for the remainder of 2004 through the start of April 2005, when the instruments were replaced.

A rapid warming in early May 2005 followed a cool April at Headwater. The ice cover at the 0.25- and 0.5-m thermistors melted in early May, with coincident warming at the 1-m sensor. Following the air temperatures,

each of these profile temperatures continued this increase throughout May. Conversely, above-freezing temperatures at the 1.5-m thermistor were stable through most of April and May. The May warming trend continued into mid-June. Then from late June through August the air temperatures were consistently cooler. Significant stratification of the upper 0.5 m of the pond at Headwater in mid-June was greatly reduced by the end of the month. After that time the 0.25- and 0.5-m temperatures closely reflected the details of the downward air temperature trend. The summer temperature at 1.5 m remained stable instead of increasing, as would usually occur with sustained high air temperatures.

Profile temperature data from the station at Upper Degraded Island were recorded at odd depths as a result of the collapse of holes drilled in the fine gray sediments at the site. The air temperature, indicated by the logger and all above-water thermistors, was highly variable on most days and without a trend from late August through mid-September 2006. Cooler temperatures with smaller diurnal variation were indicated for late September and early October. The lack of an air temperature trend over the first part of the monitored period is reflected in the 0.55-m temperatures, and the subsequent cooling trend, beginning on 25 September, is indicated. Data from thermistors at the 1.05- and 2.05-m depths show temperature increases into October and indicate annual peaks of 1.3°C and 1.1°C, respectively, at this station.

Temperature data from April through July 2007 indicated that the +0.7-, +0.45-, +0.2-, and 0.05-m thermistors were all above the water throughout the period. Each had maximum temperatures that exceeded the air temperature and had comparable diurnal fluctuations. The minimum temperature at 0.55 m was –2.7°C, which occurred at the start of the record on 3 April. The thaw at this depth occurred on 20 April, and temperatures attained a seasonal maximum of 19.1°C on 3 July. The start of the record also provided the minimum temperature of –0.8°C at 1.05 m. Thaw at this depth occurred on 14 June, and temperatures continued to increase to 6.3°C by 1 August. The 2.05-m thermistor recorded an extended period at –0.1°C from late April until late July. This temperature then began to increase, reaching 0.3°C by 1 August. Significant melting of permafrost and land surface subsidence occurred at the station during the first year of operation. The small island remnant was now submerged and part of the fen. The thawed state of the upper 2.4 m at the thermistor string allowed it

to be repositioned 0.3 m lower on 2 August 2007, submerging two additional thermistors.

Birch Island Well

At the time of drilling the Birch Island Well, 31 March 2005 (Fig. 16), the depth of permafrost at the site was 24 ft (7.3 m) from the surface. The well was drilled through the permafrost to 29 ft (8.8 m), but the collapse of coarse, unfrozen sediments at the bottom of the hole limited the well casing to a depth of just less than 18 ft (5.5 m). Development of the well after drilling (Fig. 17) indicated the desired hydraulic connection with the groundwater beneath the permafrost. Subsequent well sampling has verified the persistence of this connection, and isotope and chemical typing of the water (Ferrick et al. 2008) has demonstrated a direct relationship between the water in the nearby fen and that under the Birch Island permafrost.

Figure 16. Drilling the well through the permafrost of Birch Island, March 2005.

Water temperatures at the bottom of the well (5.5-m depth) have monotonically increased over most of the monitored period. In the weeks after installation the water refroze at the well bottom, and the temperature there began to decrease. However, on about 1 May 2005 the water temperature trend reversed, reaching a thawed state in June. For the period May through July the well temperature increased at an average rate of 0.15°C/month. Thawing of the well using heat tape allowed water sampling on 24 August, but it disturbed the temperature trend. By mid-

Figure 17. Developing and collecting initial water samples from the Birch Island Well, March 2005.

September the natural thermal condition was restored and the temperature increase continued at an average rate of 0.07°C/month for October and November, 0.08°C/month for 15 January to 15 March 2006, and 0.10°C/month for April and May. In mid-July 2006 the water temperature increased sharply and then fluctuated for the first time. Though thermal equilibrium had not yet been attained, these fluctuations may represent the first indication of short-term effects. The average rate of temperature increase between 22 June and 22 August 2006 was 0.23°C/month, the highest of the period, and the temperature at the bottom of the well exceeded 1.5°C. Over a 17-month monitoring period there was no seasonal reversal in this trend toward higher temperature. The hydraulic connection with groundwater caused by the well installation has changed the thermal condition at the 5.5-m depth from permafrost to that of the warmer sub-permafrost. Most of the losses of permafrost in the Tanana Flats have been observed to occur at fen margins, caused by efficient heat transfer from the warm water of the fens. However, monitoring of this well has been important for insight into the poorly understood processes that cause melting and degradation on the interior of permafrost islands. These well temperature data have established that groundwater exceeding 1.5°C exists beneath the permafrost of Birch Island. Movement of this groundwater beneath the permafrost and through fractures and imperfec-

tions can supply sufficient heat to cause rapid melting and degradation away from fen margins.

Ground temperatures about 3 m from the well have generally remained subfreezing throughout the monitored period, indicating a shallow active layer and stable permafrost at the site. Through the fall of 2005 these temperatures remained subfreezing and relatively constant, –0.4°C at 0.25 m, and –0.2°C at 0.5 and 0.75 m. However, temperatures at the 1-m depth were considerably lower than those nearer the surface, decreasing slowly through the fall from –5°C to –6°C. A rapid temperature decrease at 1 m occurred during January 2006, prior to corresponding decreases at shallower depths, with –9°C recorded in early February. Shallow temperature responses to this decrease occurred at 0.75 m in late January 2006, at 0.5 m in early February, and at 0.25 m in mid-February. Following a midwinter warming, the 1-m temperature minimum of –9.7°C occurred in late March. Increased depth correlated with lower minimum temperatures, also in late March, of –2.6°C, –3.0°C, and –3.7°C at 0.25, 0.5, and 0.75 m, respectively. Unlike the temperature patterns of the fens that are driven by heat flow to or from the surface, these winter permafrost temperatures appear to respond to conditions at depth. The ground temperatures all increased strongly through April, with 0.75 m and above exceeding –1°C by mid-May while the 1-m temperature increased to –6°C and then remained relatively steady into early July. Slow temperature increases at 0.75 m and above continued through late August, when all were in the narrow range of –0.55°C to –0.25°C. A series of what appear to be precipitation-event-related temperature increases at 1 m resulted in a maximum of –3.1°C by mid-August. Temperature differences between the 1-m and shallower thermistors were significant through the year.

The Birch Island temperature records were not available through the fall and much of the winter but resumed on 15 March 2007. The opposite of 2006, permafrost temperatures in late winter of 2007 were dictated by conditions at the surface. The shallow temperatures were at minimums in mid-March, with –9.5°C at 0.25 m progressively increasing to –6.1°C at 1 m. Steep temperature increases at all depths and a profile inversion occurred during April. An early June thaw at 0.25 m was followed by a continued temperature increase to 5.0°C by 1 August. Frozen conditions persisted through this period at the deeper thermistors, with maximum temperatures of –0.2°C, –0.4°C, and –0.6°C at 0.5, 0.75, and 1 m, respectively. The reason for the reversal in the direction of heat flow between

2006 and 2007 is not clear. Additional thermistors were installed on 1 August 2007 at depths of 1.5, 2, and 3 m to provide a deeper profile to more fully characterize the upper permafrost temperatures.

Temperature Profile Analysis

Several trends in the long Birch Island Fen station record apply to other stations in all fens. Large diurnal temperature changes occur during summer at shallow depths, while temperatures at deeper depths vary more gradually with features that are lagged in time from those of the shallower sensors. Near-surface temperatures are higher and more variable in summer and lower and more variable in winter than at depth, and these periods are separated by spring and fall overturns of the profile. Short-term temperature trends are initiated at the surface, decrease significantly at depths of 1 m and greater, but they can occur down to the 2-m depth. Freezing below 1 m occurred in almost all years, it but did not extend to 2 m in any year. All of these results are consistent with dominant temperature forcing at the surface, with only minor heat flux to the upper 3 m from deeper groundwater.

Common features of the Birch Island Fen data were the abrupt temperature decreases during thaw at 2 and 3 m and the abrupt temperature increases soon after thaw at 0.5 and 1 m. The abrupt temperature decreases were caused by melting and cold water migration from shallower depths. Such decreases occurred at 2 m in all five years with data for the critical period. In two of those years the decrease was also in evidence at 3 m, but it did not occur there in five other years. The abrupt increase in temperature occurred in the spring of all seven monitored years, five times at the 1-m depth and twice at the 0.5-m depth. The regularity of both features indicates the consistency of annual thermal processes at this station.

Table 2 presents a comparison of Birch Island Fen profile temperature extremes by year for the 0.5-, 1-, 2-, and 3-m depths. Because the data in most years did not extend late enough into the fall to define the temperature maximum at 3 m, the temperature on the latest common date, 11 August, is used instead. Available 3-m temperature data showed annual variability of up to 4.5°C, far from a stable condition. The maximum temperatures identify the summer of 2005 as the warmest year for the overall profile, even with the shortened record. The 0.5-m maximum for 2005 was the second highest of six, the 1-m maximum was the highest for any year,

Table 2. Birch Island Fen profile temperature extremes by year.

Year	0.5 m (°C)		1 m (°C)		2 m (°C)		3 m (°C)	
	Max	Min	Max	Min	Max	Min	11 Aug	Min
1995	25.0	–	17.1	–	11.0	–	5.0	2.5
1996	29.6*	−6.3	14.3	−1.7	9.9	0.2	4.3	2.3
1997	30.2*	−18.8	16.4	−2.8	9.8+	0.3	4.4	2.1
1998	28.6*	−6.7	14.3	−1.2	8.5	0.7	3.6	2.4
1999	–	−13.3	–	−4.2	–	0.3	–	2.1
2001	15.2	–	12.6	–	6.8	–	4.0	–
2002	18.3	–	15.6	–	7.4	–	4.8	2.0
2003	26.9	−4.3	18.2	−0.1	–	0.9	4.1	2.0
2004	21.6	−7.1	20.8	−0.4	–	–	6.1	2.1
2005	26.0	−7.9	22.7	−0.2	–	–	6.0+	2.4

* temperature ≥ shallower points, all probably out of water.

+ temperature rising at end of record on 9 July.

and the 3-m temperature on 9 July was the highest on that date by more than 1°C. Conversely, 2001 had the lowest summer profile temperatures, with the lowest maximum temperatures at 0.5, 1, and 2 m of any year, and the 3-m temperature on 11 August was second lowest of nine years. Comparing 2001 and 2005 data reveals a maximum temperature difference of 10.1°C at the 1-m profile depth and a difference of 3.0°C at the 3-m depth on July 9. The April, June, and August average temperatures at Fairbanks Airport were nearly the same in 2001 and 2005, but March, May, and July differences in average temperature were 5.4°C, 6.2°C, and 1.3°C, respectively, with 2005 always warmer. Minimum profile temperatures were not available to document the conditions immediately prior to the lowest maximum temperature profile of summer 2001. For winter 2005, the minimum temperature was moderate at 0.5 m but among the warmest at 1 and 3 m. These results indicate that winter conditions contribute significantly to temperature extremes the following summer. The minimum temperatures of Table 2 show that the freezing front progressed down to at least the 1-m depth in each winter, but the 2- and 3-m depths were never frozen. The minimum temperature data indicate that the lowest winter profile temperatures of the period occurred in 1997 and 1999. Winter air temperatures and snow cover depth and timing contribute to winter minimum fen profile temperatures, but for both of these years, the preceding summer maximum profile temperatures were generally below the median at all depths. Just as winter conditions influence the following summer, the thermal storage in the fen from the previous summer is important to temperature conditions the following winter.

Table 3. Murphy Station temperature profile comparisons (°C).

Date	1 m	2 m	3 m
1 April 2004	1.0	1.8	2.1
1 April 2005	2.3	2.8	3.1
1 April 2006	–	–	–
1 April 2007	–1.6	0.9	1.6
1 September 2004	10.2	5.9	4.2
1 September 2005	11.9	7.2	4.7
1 September 2006	7.6	2.1	1.9

The 1-, 2-, and 3-m Murphy profile temperatures at the end of winter (1 April) and at the end of summer (1 September) are compared for 2004–2007 in Table 3. Each summer month of 2004 was warmer than the corresponding long-term average, and temperatures between 1 April and 1 September increased 9.2°C, 4.1°C, and 2.1°C at 1, 2, and 3, respectively, in response to surface heating. Heat loss during the winter of 2004–05 was inadequate to return the 1 April 2005 temperatures to the starting point of 2004. Residual temperature increases over the year were between 1°C and 1.3°C at these depths, averaging 1.1°C. This residual heat was preserved through the summer 2005, a significantly cooler summer than 2004, though still slightly warmer than the long-term average. The same comparison for 1 September 2005 yields almost the same average temperature increase of 1.2°C for the profile. However, the 1 September 2006 temperatures indicate a major cooling of the profile by an average of 4.1°C from the previous year. The lack of temperature profile data for the spring of 2006 does not allow the heat loss during the intervening year to be attributed to a particular season. Much lower air temperatures in the summer of 2006, compared to 2004 and 2005 (Table 1), contributed to this significant heat deficit. Summer air temperatures were lowest in 2006, highest in 2004, and intermediate in 2005, while 1-, 2-, and 3-m temperatures on 1 September were lowest in 2006, highest in 2005, and intermediate in 2004 at each of these depths. Following the lowest summer profile temperatures of 2006 were the lowest winter profile temperatures of April 2007. The short Murphy temperature profile record supports the Birch Island Fen results, with both showing that large thermal shifts can occur in consecutive years. The thermal state of the Upper Fen in a given season is a consequence of that existing in the previous season, in addition to temperature and snow cover conditions of recent months.

Pond temperature trends at the Upper Fen Headwater station were much like the fen temperatures at Birch Island and Murphy. Minimum temperatures at 2 and 3 m in the sediments below the pond were always above freezing, 0–1°C, but lower than those of other Upper Fen locations at these depths. Similarly, maximum temperatures of 3–4+°C at 2 m and 2–3+°C at 3 m were lower than those at comparable Birch Island fen and Murphy fen depths. August temperatures of 0.3°C at the 2.05-m depth at Upper Degraded Island are probably a result of proximity to remnant permafrost. The only Upper Fen temperatures at 2 m lower than these were in the permafrost near the Birch Island well, where temperatures at and below 0.5 m have remained subfreezing throughout the year.

Water Level Measurements

Water level measurements will be used to quantify mat submergence in both fens used by airboats. Controlled traffic studies (Ferrick et al. 2008) have shown that high water levels over the emergent fen vegetation protect the mat from damage by airboats. Therefore, a science-based management plan, protecting and preserving the hydrological and ecological resources of the Tanana Flats, will require long-term water level records to optimally define minimum water levels for airboat use. An interim management plan will need to rely on data obtained to date.

Murphy Fen

The initial water level monitoring at Murphy station began on 11 July 2003 during a dry period with low fen water levels that corresponded to no surface outflow from the Upper Fen. In response to several significant rainfalls, these levels began a strong upward trend through July and into August, initiating fen outflow and then peaking at an overall rise of 1.3 ft (0.40 m). The thermal mixing of the upper 0.5 m coincided with the rapid stage increase and initial throughflow in the fen during late July. The stage trend reversed in August, and levels fell through the end of the monitored period, a net decrease of 0.46 ft (0.14 m) from the peak.

Fen water levels at the reestablished Murphy station, for the period of April 2004 through June 2005, are given in Figure 18 and summarized in Table 4. The fen water level in late winter 2004 began at a low point that corresponded to no surface outflow from the Upper Fen. Then, from an annual peak during April melt, the water levels at Murphy generally diminished through August, in response to extremely low rainfall. Compared to other

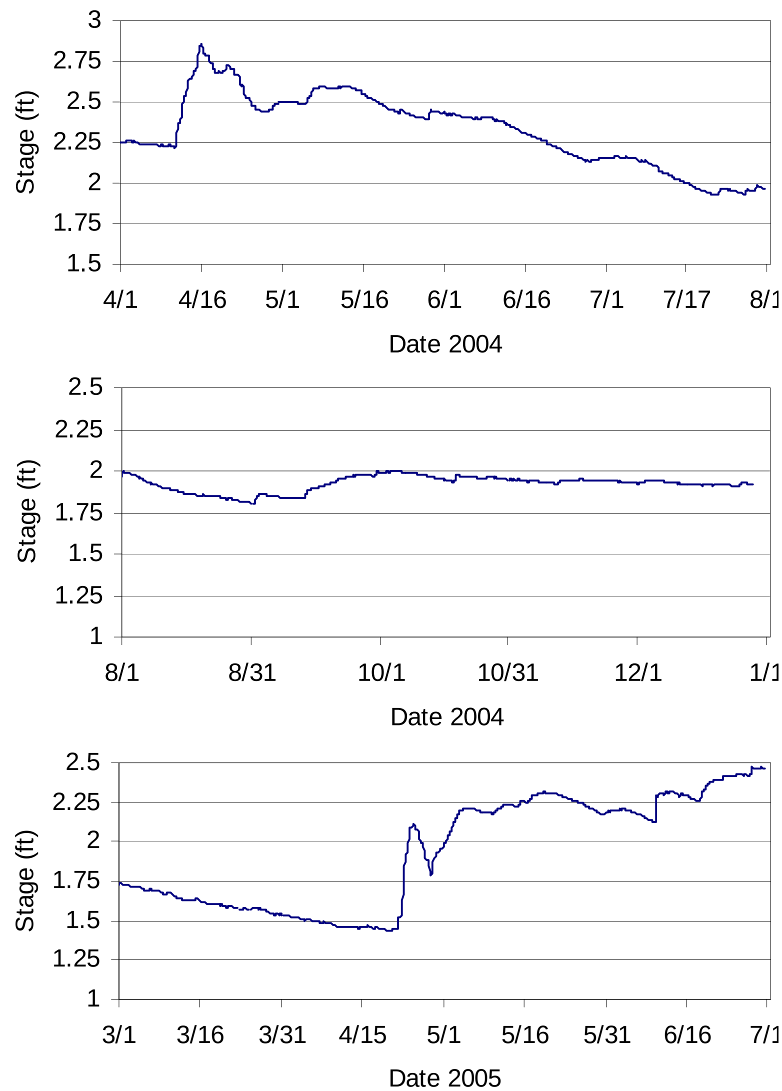

Figure 18. Stage at the Murphy Fen station, April 2004 through June 2005.

months, August had the lowest mean water level and the annual minimum level. Water level variability, represented as a standard deviation by month, was greatest in April and generally diminished through the year, with a minimum in November. Maximum monthly water levels decreased monotonically from April through December. The fen water level range at Murphy station in 2004 was 1.05 ft (0.32 m), less than that of July 2003. Stage recession at Murphy continued from 1 March through 21 April 2005 (Fig. 18), when the fen level reached a minimum 1.44 ft (0.44 m). Then in response to spring melt, the stage rapidly increased to a peak of 2.11 ft (0.64 m) on 25 April. For the tabulated period of 2004–2005, April was the month with the largest stage variability in both years. The overall maximum level occurred in April 2004, while the overall minimum level was in April 2005. The stage increase during early May to a peak of 2.31 ft

(0.70 m) on the 19th was followed by a gradual decrease to 2.12 ft (0.65 m) on 10 June. The April and May peak stages of 2005 were lower than those of 2004 by 0.75 ft (0.23 m) and 0.29 ft (0.09 m), respectively. The continued rise in water levels during June 2005, equal to the levels of June 2004, erased the remaining hydrologic deficit. A continuation of this rising stage trend through July 2005, with a peak of at least 3.0 ft (0.91 m), produced stages 0.5 ft (0.15 m) higher than the maximum of 2004, flooding the Birch Island fen logger.

Table 4. Murphy Station 2004–2005 water level data summary.

Month	Mean ± Std Dev (ft)	Maximum (ft)	Minimum (ft)
April 2004	2.44 ± 0.20	**2.86**	2.22
May	**2.50** ± 0.07	2.60	**2.39**
June	2.30 ± 0.10	2.44	2.14
July	2.04 ± 0.09	2.16	1.93
August	1.88 ± 0.05	2.00	1.81
September	1.90 ± 0.06	2.00	1.81
October	1.97 ± 0.02	2.00	1.94
November	1.94 ± **0.01**	1.95	1.92
December	1.92 ± 0.01	1.94	1.90
March 2005	1.63 ± 0.06	**1.73**	1.53
April	**1.60 ± 0.21**	2.11	**1.44**
May	2.22 ± 0.07	2.32	1.96
June	2.30 ± 0.10	2.47	2.12

Bold represents an extreme for this period.

Rainfall was recorded together with stage at Murphy station starting in late August 2006. Through 2 August 2007 most rainfalls were very light, with only six events in late May through July that exceeded 1 cm. The fen stage had small amplitude variability but remained very stable throughout the almost year-long period. Most of the 0.5 ft (0.15 m) net decrease in stage occurred during the winter, followed by very little stage response to melt or the few summer rainfalls.

Upper Fen Headwater–Upper Degraded Island

Water levels at the Upper Fen Headwater station were stable in the fall of 2003, with small fluctuations and a very gradual downward trend from late September to late November. The relatively large water level increase that followed into December was due to some combination of snow

accumulation and freezing near the probe. Water levels at Headwater in the spring of 2004 show a decrease in late March followed immediately by a melt-induced rise during the first half of April and a peak in mid- to late April. These elevated levels gradually diminished during May and then remained steady into August. Unlike the Murphy station, the very dry summer of 2004 did not cause the water levels at Headwater to diminish, indicating that the local water supply to this pond balanced the outflow and evapotranspiration losses. With very limited rainfall, the implication is that these water levels were maintained by a significant local source of groundwater. Instrument failure at the Headwater station in the fall of 2004 required redeployment in April 2005. Inflow due to melt in late April produced a much smaller peak at 2.47 ft (0.75 m) than in the previous year. Recession was slow and gradual during May, and water levels were stable at 2.3 ft (0.70 m) through mid-June. An abrupt increase in stage occurred in late June, and rising stages continued to a late July peak level of 2.95 ft (0.90 m). High water levels were maintained in August with only a minor recession, and late August field work confirmed these high levels throughout the Upper Fen. Winter water levels were stable in March through early April 2006, prior to the onset of melt, fluctuating only 0.1 ft about the mean.

Two water level sensors were installed in August 2006 at Upper Degraded Island. The sensors show water levels diminishing by 0.27 ft (0.08 m) into the fall from the high water of August. Both sensors were frozen when data resumed in early April 2007, and sensor #2 remained erratic and did not recover. Sensor #1 appeared to recover in late May and showed almost steady water levels with a slow 0.3-ft (0.09-m) decrease from then through 2 August.

Birch Island Well

The water level in the Birch Island well was drawn down during initial development and sampling, prior to installation of a Druck pressure transducer near the bottom. In response to this drawdown, the initial record showed a water level of 1.13 m on 1 April 2005, which gradually increased to 1.68 m on 8 April. Freezing of the sensor on 9–10 April ended the reliable water level record. A pair of replacement Drucks, installed on 26 August 2005, indicated a flat stage response for about a week before freezing began. After freezing, the water level data from these two sensors had smooth and nearly identical trends from mid-September 2005 through August 2006. Water levels decreased throughout the winter to a minimum

stage on 1 April, just prior to melt. The water level trend then reversed with a smooth rise to a mid-June peak, followed by a recession through August. It is not clear whether these sensors properly represented the water level trends in the well. No water level data were obtained at Murphy during this period to compare with those of the well. A survey of water levels of the well and of the fen on 22 August 2006 found them equal, supporting the finding based on water tracing of a direct hydraulic connection. The water in the well was then sampled again, and a new Druck was installed to replace those that had been frozen. With rising temperatures at the bottom of the well, an injection of 400 g of table salt was made to help prevent the freezing of this replacement Druck.

In August 2007 there was no ice in the permafrost zone of the well, indicating that over the prior year the water level had not equilibrated with that of the fen. The water level in the well decreased smoothly from 0.25 m on 15 March 2007 to 0.09 m on 19 May and then smoothly increased through 1 August, when it reached 0.45 m. There was no indication of sensor freezing in these data, and the well sensors were not frozen on 1 August. Water level recovery following this August sampling was very slow and barely measurable, even though the level was more than 3 m below that of the local fen. The hydraulic conductivity near the well screen had clearly diminished in 2007 relative to that immediately after installation in 2005. The water level increase in the well was 0.36 m from mid-May though July, a period of about 75 days. The water level of the adjacent fen increased 0.39 m from 21 March through 27 June, a period of about 95 days. Direct comparison of these records indicates similar increases in level and overall rate at both locations, with about a two-month lag between changes in the fen and the response of the well. Our hypothesis is that the developing thaw at the bottom of the well has induced a significant reduction in hydraulic conductivity, which has compromised the connectivity with groundwater.

Water Level Analysis

Water levels in the Upper Fen follow an annual cycle. Slow recession occurs as a result of outflow during the cold late fall and winter months, and spring melt is a time of recharge and water level recovery. Water levels in May through October vary significantly between years, depending on rainfall during the period. Hydrologic deficits that develop in dry years can be erased in one to two wet months. Data from the station pair at Birch

Island Well–Murphy Fen indicate a direct connection throughout the year between water beneath the permafrost and that in the nearby fens.

In summer 2003 several significant rains increased the Upper Fen water level by 1.3 ft (0.4 m) in less than a month. However, the resulting high water levels decreased rapidly following cessation of rainfall due to large surface outflows. Surface outflows diminish as water levels fall, and moderate levels can be sustained by normal rainfall. At the opposite extreme, three very dry summer months during moderate to low water conditions in 2004 led to a decrease in Upper Fen water levels of 0.63 ft (0.19 m). Based on data collected to date, the full range of Upper Fen water levels exceeds 1.5 ft (0.5 m). At high water the fen vegetation is largely submerged, and travel by airboat is easy and without lasting impacts. Conversely, at the lower end of the level range, airboat damage to root mats can require several years for recovery. Murphy station water levels represent a larger part of the Upper Fen than those of the Upper Fen Headwater/Upper Degraded Island station. Therefore, management of Upper Fen access by water levels should be based on measurements at Murphy station. The staff gauge depicted in Figure 9 will provide consistent water level measurements that are needed for management of airboat access to the Upper Fen, as long as it remains undisturbed.

4 Lower Fen

Temperature Profile Measurements

Lower Fen Headwater

The Lower Fen Headwater station was established on 25 August 2005 with only a water level sensor external to the logger (Fig. 19). A 3–m temperature profile was added to the station on 19 July 2006. Logger estimates of air temperatures at this station were variable in March 2006, though consistently below freezing, while April temperatures were high enough during most of the month to produce significant melt. Continued warming during May resulted in high temperatures approaching 30°C by the end of the month. With the exception of a cold period in early June, warm summer conditions persisted through July. Air temperatures exceeded 30°C in July before gradually cooling in the fall to –16°C by early November.

Figure 19. Lower Fen Headwater installation, August 2005.

The thermistor at the 0.25-m depth closely reflected the air temperature trend, with a peak of 15.4°C in late July, cooling to below 0°C by the start of November. A large temperature increase at the 0.5-m depth from only 1.5°C in mid-July to a peak of 10.4°C in mid-August was followed by a

gradual temperature decrease through the end of the period. This record, like that for 0.25 m, contains short-term variability that was not present for the deeper thermistors. At 0.75 m the temperature increased smoothly from less than 0.2°C in late July to a peak of 7.2°C in late August. This temperature then decreased gradually through late September and more rapidly into the fall. The 0.75-m data record is shaped very similarly to that at 0.5 m except for reduced amplitude, a lag in time, and a lack of short-term fluctuations. The temperature records at 1 and 1.5 m had a similar relationship to the shallower pair at 0.5 and 0.75 m. The deeper thermistor showed a more gradual temperature increase to a lower peak later in the season. A temperature of 1°C at 1 m in late July increased to a peak of 5.1°C in late September and then began a rapid decline in October. At the 1.5-m depth the 1°C late July temperature increased to a 4.2°C peak in early October. Still deeper, the 2-m temperature increased from 1.6°C in late July to a broad annual peak in mid-October of 3.5°C. The temperature at 3 m remained constant at 1.3°C through the summer to fall period and is probably indicative of deeper local groundwater.

Sunken Stream

The Sunken Stream station is located on an outlet stream from the Lower Fen that transits an uplifted area underlain by permafrost to connect with a slough of the Tanana River (Fig. 20). The view upstream from the station in Figure 21 shows the stream, typically about 2 m in depth at normal water levels, incised through the permafrost with a narrow width and high, steep banks. This station was established on 24 August 2004, with only the water level sensor and logger temperature providing reliable data. Air temperatures decreased during late August through mid-September 2004, held constant until mid-October, and then decreased toward the end of the year. The temperature remained below freezing, and diurnal fluctuations did not occur after 19 October.

Wide temperature variations, from near freezing to less than −40°C, occurred in January and February 2005. A warming trend in early March was followed by sustained milder temperatures through early April. Consistent above-freezing temperatures in late April and early May indicate the snowmelt period. Temperatures from late May through mid-August were relatively consistent, followed by cooler conditions from late August through the end of the record on 16 September.

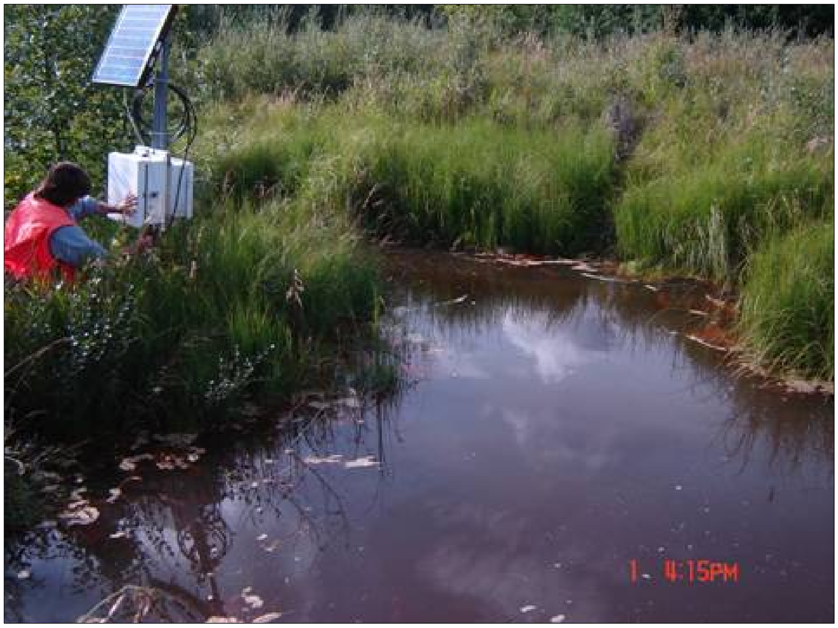

Figure 20. Sunken Stream station, looking downstream, August 2007.

Figure 21. Sunken Stream station, looking upstream, August 2007.

The station instrumentation was restored on 13 January 2006, including a temperature profile to a depth of 3 m. Consistent cold in January was followed by a mild February, with several above-freezing high air temperatures, but March temperatures remained below freezing. Profile temperatures at 0.25 and 0.5 m followed the air temperature trends, while temperatures at 0.75 and 1 m were stable through this period. Profile temperatures at 2 and 3 m diminished through January and February to minimums of -0.03°C and -0.1°C, respectively, in March. Daily average air temperatures increased almost linearly from about 0°C in late April to 10°C at the end of May, and these late-May temperatures were sustained through June. The profile temperatures each increased gradually during April to approach an isothermal condition at the end of the month. On 1 May the entire thermistor string began recording large-amplitude fluctuations with similar temperatures at all depths, indicating removal from the stream (probably during breakup of the ice) and the end of useful profile data.

The station instrumentation was again restored on 21 July 2006, including a seven-thermistor temperature profile. Logger and profile temperatures for July through September 2006 are presented in Figure 22. Air temperatures remained high until late July and then progressively decreased through late September. Profile temperatures at 0.25, 0.5, 0.75, 1, and 1.5 m all had similar values and the same decreasing trend through the period. The 0.25-m temperature displayed the largest fluctuations and the most rapid response to cooling of the air. This agreement shows that the stream was well mixed in the upper 1.5 m. The heat in the flowing water did not transfer efficiently into the streambed, as temperatures at 2 and 3 m were stable and much lower throughout this period than those at and above 1.5 m. A progressive decrease in air temperature from above freezing to –34°C occurred during late October to late November. Subfreezing temperatures progressed down the profile to 0.25 m by mid-October, 0.5 m by early November, and 0.75 m by mid-December. Deeper temperatures down to 3 m remained above freezing through the end of 2006, but all minimum temperatures were below 0.5°C.

Air temperatures increased toward the end of January 2007, decreased through February, and then increased again through March, remaining subfreezing until the end of this period. Profile temperatures at 0.25, 0.5, and 0.75 m were all subfreezing through the period, increased with depth, and responded to short-term changes in air temperature. The 1-m temperature became subfreezing in early January, remained nearly

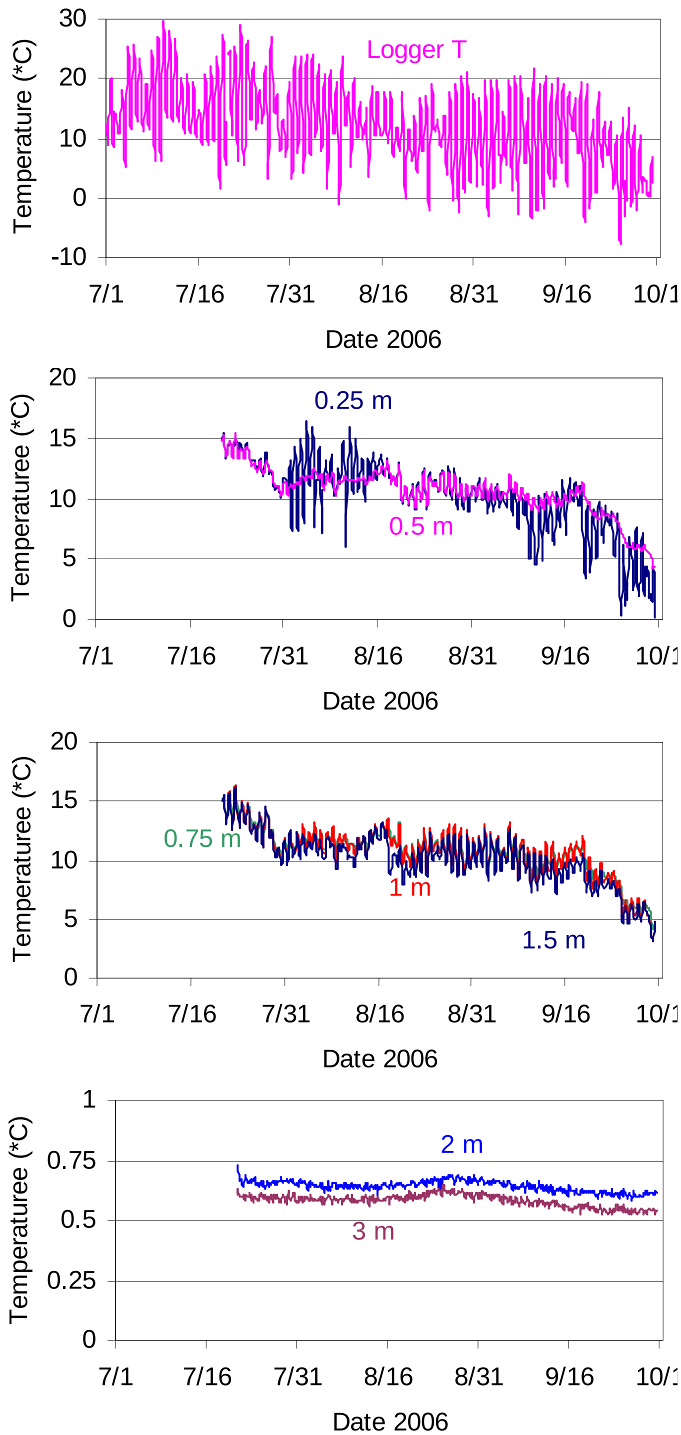

Figure 22. Logger and stream profile temperatures at the Sunken Stream station, July–September 2006.

constant until late February, and then decreased through March to −0.7°C. The deeper 1.5-, 2-, and 3-m temperatures decreased almost linearly with time during January–February, but all remained slightly above freezing. Air temperatures steadily increased through April–May, with significant

melt indicated by mid-April. Profile temperatures indicated concurrent melt from both above and below, beginning at 0.25 and 1 m on 19 April and continuing to 0.5 m on 23 April. Profile temperatures at 0.25 m were generally highest during the summer, but stream mixing was again effective down to 1.5 m. Maximum summer temperatures were 25+°C at 0.25 and 0.5 m, while 0.75- to 1.5-m temperatures peaked at 18–19°C. In contrast, summer temperatures in the bed at 2 and 3 m generally remained below 1°C, indicating close proximity to permafrost.

Willow Creek Fen

The Willow Creek Fen station, located near a primary outlet of the Lower Fen, was established on 26 August 2004, with only the water level sensor providing reliable data. A view of the fen from near the station is given in Figure 23. The logger temperatures and temperature profile to a depth of 3 m were restored on 10 June 2005. Diurnal air temperature fluctuations were large throughout this summer, which included three significant cool periods in late June, late July, and late August. These summer temperature trends can be more clearly seen in the 0.25-m temperatures that are not masked by the diurnal fluctuations. The annual peak temperatures at the 0.25- and 0.5-m depths of 16.4°C and 8.3°C were both attained on 18 June. The temperature at 1 m had a broad and flat peak of 6.0°C extending

Figure 23. View of Willow Creek fen from near the station, August 2005.

through the period of 12–24 July, followed by minimal temperature recession through August. The deeper temperatures at 2 and 3 m did not yet attain annual peaks by August, with both showing slow temperature increases to 4.9°C and 3.7°C, respectively, near the end of the month.

All profile temperatures were lost near the end of August 2005, but the logger temperature record continued through the fall. Air temperatures remained above freezing during September but decreased significantly through October and into November, when the record ended. The logger temperature record resumed in January 2006 and indicated above-freezing high temperatures in February. Spring warming began in mid-March, and melt-producing temperatures were attained in April. This general warming trend continued through May, with peak air temperatures in June through early August.

A replacement array of profile temperature sensors was installed on 24 August 2006. Air temperatures were stable into late September, when a cooling trend began that extended into November. The final above-freezing air temperature was recorded on 24 October. The thermistor at the 0.25-m depth closely reflected this air temperature trend, with diurnal temperature fluctuations continuing well into October and freezing conditions starting on 23 October. Temperatures at the 0.5-m depth lagged those at 0.25 m, were without diurnal variations, and indicated the start of freeze-up on 3 November. At 0.75 m the temperature increased to an annual peak of 3.8°C on 19 September and then began a significant decrease into the fall. The 1-m temperature increased gradually to a peak of 2.3°C on 24 September and then decreased through the fall. The 0.75- and 1-m temperatures were both 1.2°C on 17 October, and afterward the temperatures inverted. The temperature records at 1.5 and 2 m both had broad annual peaks in the fall. The 1.5-m temperature peaked at 1.0°C from 24 September until 8 October, and the 2-m temperature peaked at 0.8°C between 29 September and 21 October. Continuing the trend with increasing depth, the 2-m thermistor had a more gradual temperature increase to a lower peak that occurred later in the season than the 1.5-m thermistor. These temperatures were equal at 0.7°C on 23 October and then inverted. In contrast to these records, the temperatures at 3 m were erratic and may not be reliable.

Air temperatures in 2007 were subfreezing until late March and then were consistently above freezing in mid- to late April. Continued warming

occurred in May through mid-June, followed by peak temperatures in late June through July and slightly decreased temperatures in August. The 0.25-m thermistor was out of the water from April into June, allowing large diurnal fluctuations, comparable to those of air temperature, to occur. At 0.5 m the temperature remained near 0°C during mid- to late April, increased above freezing in early May, and attained a seasonal peak of 11.3°C on 3 August. Freezing temperatures persisted later in the season with depth- as the 0.75-, 1-, and 1.5-m thermistors indicated complete melt on 1 June, 11 July, and 12 August, respectively, with the end of the record on 13 August. Minimum temperatures at 2 and 3 m were just above 0.0°C and 0.2°C, respectively, with both occurring in July. The 1-, 2-, and 3-m temperatures in August 2007 were very close to those of August 2006 but about 4°C below those of August 2005.

Temperature Profile Analysis

Lower Fen Headwater temperatures in 2006 were unique in that the entire profile below 0.25 m was at 1.6°C or less into July, followed by strong warming that progressed in depth with time. Another unique feature was that the 3-m temperature was constant at 1.3°C throughout the summer–fall period. The stream at the Sunken Stream station was well mixed through the upper 1.5 m during the summer, while the bed temperatures at 2 and 3 m were much lower. Sunken Stream was the only station where seasonal freezing has progressed down to 3 m during the winter. Dynamic stream processes during spring breakup of the ice makes long-term survival of instruments at this station problematic, and thawing–collapsing stream banks threaten the station itself. The temperature profile records from 2005 and 2006 at the Willow Creek Fen station do not have a seasonal overlap. However, temperatures on 25 August 2005 at 1, 2, and 3 m were 4.7°C, 4.1°C, and 2.9°C higher, respectively, than those at the same depths on this date in 2006, and the lower temperatures of 2006 were very nearly duplicated in 2007. Annual differences of this magnitude, also observed at other stations, are significant. The average 1-, 2-, 3-m profile temperature difference at Willow Creek of 3.9°C compares closely with 4.1°C at Murphy in the Upper Fen (Table 3) for nearly the same dates in 2005 and 2006. The profile temperature differences at the Willow Creek Fen station show that, like the Upper Fen, a very large change in the thermal state of the Lower Fen can occur in one year.

Water Level Measurements

Lower Fen Headwater

The Lower Fen Headwater station was established on 25 August 2005 with only a water level sensor external to the logger. Water levels at this station varied throughout March 2006 by up to 0.2 ft (0.06 m), with little net change for the month. April water levels had an upward trend as a result of melt, peaking near the end of the month at just over 4.5 ft (1.37 m). The upward trend in water levels reversed in May and early June as levels fell steadily with a net decrease of 0.7 ft (0.2 m). This entire water level decrease was then matched on a single day, 18 June, when an abrupt decrease was followed by a temporary recovery and then a second decrease. These data indicate a significant event near the station of an unknown nature. From 19 June to 8 July the water level increased 0.53 ft (0.16 m), followed by another 0.7-ft (0.2-m) decline in water level, yielding a stage of 3.0 ft (0.91 m) by the middle of July. Mid-July temperatures at 0.75 m near 0°C indicate the persistence of a frozen layer near that depth. Melting of such a layer could allow surface water to rapidly replenish depleted local groundwater and may be related to the mid-June or mid-July water level decreases. Additional data are needed to better understand the cause(s) of rapid water level change at this station during the summer.

A backup water level sensor was added to the station on 19 July 2006. Water levels recorded at both sensors varied ±0.1 ft (0.03 m) about their respective means for the remainder of July through October, with very little net change. A gradual stage increase of 0.35 ft (0.11 m) was indicated by both sensors in November, followed by recession into December. These water level trends are in good agreement until 16 December, when sensor #1 showed an increase while sensor #2 showed a continued recession, a difference in trends probably caused by freezing near sensor #1. Both sensors show slowly decreasing stage in January and February 2007. Sensor #2 was then frozen and subsequent records were invalid. Sensor #1 indicated variable water levels about a stage of 4 ft (1.22 m) from mid-March through April and then variable and slowing diminishing levels to 3.4 ft (1.04 m) in August. Reliable records from sensor #1 ended abruptly on 7 August.

Sunken Stream

The stage record for Sunken Stream in 2004 indicates a gradual recession into the fall, from 5.5 ft (1.7 m) on 24 August to 4.6 ft (1.4 m) on 31 October. During November and December the stage increased progressively from this minimum to 6.2 ft (1.9 m) by the end of the year, probably a result of ice growth and accumulation in the channel. Stream stage continued to increase into January 2005, peaking at 7.0 ft (2.1 m) late in the month. Afterward, a high stage was maintained until an abrupt decrease to 4.2 ft (1.3 m) occurred on 1 May 2005, due to breakup of the ice cover in response to spring warming and melt-induced flow increases. Stage peaks during the summer period on 2 May at 5.0 ft (1.5 m), on 22 June at 3.9 ft (1.2 m), and on 21 July at 4.3 ft (1.3 m) were each followed by recessions. Because of the free-flowing nature of the stream, these open water stage records should correlate with discharge from the fen. The stage sensor was repositioned deeper in the stream on 25 August, and after that date, stage remained low and stable until the end of the record on 16 September.

Stage fluctuations in January through March 2006 followed those of temperature with a time lag, possibly corresponding to freezing and thawing of source areas in the watershed. A slow stage rise in mid-April followed the initiation of above-freezing temperatures at the beginning of the month. Intensified melt in late April produced larger stage increases. From the peak of 5.06 ft (1.54 m) on 30 April, the stage decreased to 4.23 ft (1.29 m) on 1 May and to 3.91 ft (1.19 m) on 2 May. This falling stage, caused by melt and breakup of the ice in the stream near the station, coincided with the extraction of the thermistor string from the stream. The water level sensor was also lost several days later, on 8 May. The station instrumentation was restored on 21 July 2006, including a pair of redundant water level sensors. These sensors showed generally increasing stage through the end of the month, but on 1 August both sensors recorded an abrupt drop in water level of 1.44 ft (0.44 m) in 8 hours. Removal of material blocking stream flow just below the station or a new channel blockage upstream of the station could have caused this drop. Both sensors then showed gradually increasing stage and flow to a second peak on 21 August, with general recession afterward through early November. Stage increased by 2.3 ft (0.70 m) through the remainder of November, with steady levels in December. The increasing stage in November was likely a result of aufeis development in the stream. The progressive nature over several weeks of this stage increase was too long to be associated with dynamic flow processes and too short to be caused by thermal growth of floating ice.

Stream stage receded slightly during January 2007 before the sequential freezing of the sensors on the 19th and 28th. Prior to freezing, the sensors were in excellent agreement, supporting the reliability of the data obtained. Thaw of both sensors allowed data acquisition to resume on 20 April, again with excellent agreement that was sustained until their ultimate failures in July. Stream stage fell from that at the resumption of the record, rapidly at first and then more gradually, for a total decrease of 2.52 ft (0.77 m) by 28 May. Stage then recovered 1.27 ft (0.39 m) by 9 June, decreased 0.72 ft (0.22 m) by 23 June, and then increased 1.26 ft (0.38 m) by 10 July, a total net decrease of 0.71 ft (0.22 m) from 20 April. Several events occurred in the stream near the station in a three-day period of generally increasing stage, 1–3 June, with four abrupt stage increases totaling 1.5 ft (0.46 m) and an abrupt stage decrease of 0.94 ft (0.29 m). Failure into the stream of unstable banks near the station, due to melting permafrost, is a suspected cause of these varialbe water levels.

Willow Creek Fen

Willow Creek Fen above the outlet to Willow Creek is depicted in Figure 23. The stage record for the Willow Creek Fen station started on 26 August 2004 and showed a gradual recession into the fall, with an overall range of 0.6 ft (0.18 m). The station was without power during the winter, but when data collection resumed in April 2005, the stage had not changed appreciably from the previous fall. Then, in response to melt, the stage increased steadily from 5.6 ft (1.71 m) on 22 April to a spring peak of 7.3 ft (2.23 m) on 1 May. A gradual recession followed this peak, extending through May and into early June. Summer rainfall produced a gradual stage increase to a peak of 6.9 ft (2.1 m) on 20 July, followed by an extended period of recession that continued through August. The stage of Willow Creek Fen was stable in September, before receding through the remainder of fall 2005.

Stage records for the fen resumed in January 2006, and the complete record for the year is given in Figure 24. Low and constant stage persisted through the winter months prior to the melt-induced stage increase that began on 20 April at a stage of 4.36 ft (1.33 m). By 28 April the stage reached 5.52 ft (1.68 m), with the spring peak following on 6 May at 5.94 ft (1.81 m). Apart from the water level recession of late May through mid-June, the summer levels remained high. The fen water level reached 6.11 ft (1.86 m) and was nearing a summer peak on 21 August, when the record ended. A replacement pair of water level sensors was installed and began

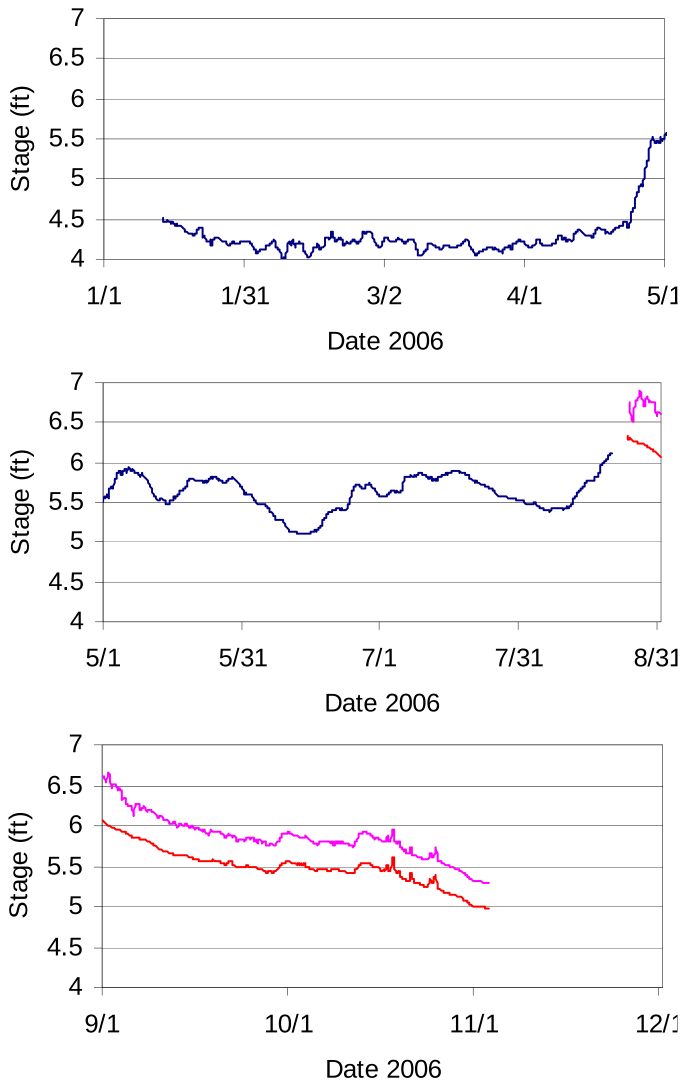

Figure 24. Stage at the Willow Creek Fen station, January–October 2006.

recording on 24 August 2006. By that date a slow water level recession had begun that continued through the following month. Water levels were then constant from late September until recession resumed in late October, probably a result of freeze-up in the watershed. The new water level sensors were in good agreement throughout the fall of 2006.

The 2007 stage record indicated a recession of 0.61 ft (0.19 m) from 25 January through 31 March. A melt-induced stage increase began on 11 April, peaking on 27 April at 1.5 ft (0.46 m) above the stage at the start of the month. A recession of 0.83 ft (0.25 m) from this peak bottomed on 24 May, prior to a protracted increase of 1.99 ft (0.61 m) to a summer peak on 9 August. A staff gauge for daily web camera viewing and stage measure-

ment at the Willow Creek Fen station, shown in Figure 25, was installed on 2 August 2007.

Figure 25. Staff gauge at Willow Creek Fen station for daily (May–September) water level measurement and posting with a web camera.

Water Level Analysis

Initial monitoring at the Lower Fen Headwater station from 2006 produced a water level range of 1.6 ft (0.49 m), comparable to that of other Lower Fen stations over the same time period. The stage at Lower Fen Headwater was flat in 2007, with a slow recession during the summer. Water levels at Lower Fen Headwater are characteristic of only the local area, though they probably also represent other fen headwater areas. The Sunken Stream station has displayed the most dynamic water levels and the largest range, 5.7 ft (1.7 m) in 2005, of any station in the Tanana Flats. Ice growth causes significant staging over the winter, and stream breakup in April to early May is associated with rapid and large water level fluctua-

tions. When the channel is unobstructed by ice or debris, the discharge is directly related to station water level. The stage range at Willow Creek station from a maximum in 2005 to a minimum in 2006 was 3.3 ft (1.0 m). Water levels at Willow Creek increased 2.7 ft (0.81 m) during April through August 2007, the only station in the Tanana Flats with a significant increase during this period. Water levels at Willow Creek represent a sizable fen environment, are related to the nearby surface outflow, and are sustained by a large upstream watershed. As a result, Willow Creek provides the best overall perspective on Lower Fen water levels for management of airboat access.

Four common data recording periods are available to compare water levels between the Upper Fen Murphy and Lower Fen Willow Creek stations. The first is August 2004 through the end of the year. Following a very dry summer, the water levels at Murphy receded in August and then remained flat for the rest of the year. At Willow Creek the recession in levels continued through the end of October, an additional two months before becoming flat. An abrupt water level rise in response to melt began on 23 April 2005 at both Murphy and Willow Creek. However, the peak stage at Murphy on 26 April preceded that at Willow Creek, which occurred on 2 May. Water levels at Murphy were high through May, while Willow Creek levels receded. In June the levels at both stations steadily increased as a result of precipitation. During the fall of 2006, the third common data period for these stations, the levels at Murphy were flat, while those at Willow Creek receded. Assuming comparable precipitation on both watersheds, the longer Willow Creek response times represent those of a much larger basin, consistent with surface discharge differences between the Upper Fen and Lower Fen (Ferrick et al. 2008). Spring melt in 2007 and several small rains at Murphy in June–July caused a variable stage at Murphy of ±0.5 ft (±0.15 m) without a seasonal trend. Conversely, both the melt and summer rainfalls caused significant stage increases at Willow Creek in 2007. Field observations have inferred a larger groundwater inflow to the Lower Fen relative to that received by the Upper Fen. As a result of all these differences, it is prudent to manage airboat access to these fens separately, with local measurements at both stations.

5 Crooked Creek Fen

The Crooked Creek Fen is the farthest from Fairbanks of the monitored fens and has not been used by airboats. This newest station near the fen outlet (Fig. 26) was installed on 25 August 2006, with temperature profile and water level sensors. It serves as an undisturbed control to compare with the other fen stations.

Figure 26. Crooked Creek Fen station after installation, August 2006.

Temperature Profile Measurements

The local air temperatures at Crooked Creek Fen were largely above freezing from the time of station installation through mid-October 2006. These mild conditions were followed by a strong cooling trend to winter conditions by mid-November and continuously subfreezing temperatures through the end of the year. Profile temperatures on 1 September at 0.25, 0.5, 0.75, and 1 m were 7.2°C, 6.1°C, 5.1°C, and 3.9°C, respectively. Each of these temperatures decreased through the remainder of 2006, with a profile inversion in mid-October. Annual maximum temperatures at 1.5, 2, and 3 m of 2.9°C, 2.2°C, and 2.0°C, respectively, occurred sequentially with depth in late September and early October. Afterward, these deeper temperatures decreased, with the profile inverting on 31 October and temperatures clustered between 0.25°C and 0°C at the end of 2006.

Air temperatures in 2007 remained subfreezing until the end of March. Short term (days) trends in air temperature during this period were reflected in the 0.25-m profile temperatures but were much more attenuated in the 0.5-m temperatures. Deeper temperature records displayed only seasonal trends. Annual minimum temperatures of –9.3°C on 26 February, –4.5°C on 7 March, –2.8°C on 20 March, and –1.3°C on 31 March were recorded at 0.25, 0.5, 0.75, and 1 m, respectively. Temperatures at 1.5, 2, and 3 m all diminished through this winter period toward annual minimums in April of –0.3°C, –0.1°C, and 0.1°C, respectively. Air and profile temperatures for April–July at the Crooked Creek Fen station are given in Figure 27. Air temperatures increased steadily through April and May toward summer conditions in June–July. Thaw progressed downward through the profile, reaching 0.25 m on 15 May, 0.5 m on 16 June, and 0.75 m on 14 July. Subfreezing conditions persisted through 2 August at 1, 1.5, and 2 m, and the temperature at 3 m remained near its annual minimum. The only profile temperature to reach an apparent annual maximum during the monitored period of 2007 was 22.2°C at 0.25 m on 30 July.

Water Level Measurements

The water level sensors indicated a 1.6-ft (0.49-m) stage increase at Crooked Creek Fen station in September 2006, followed by a gradual recession of 1.2 ft (0.37 m) through mid-November, when the sensors were frozen. When the water level records resumed in early 2007, the levels were steady and receding slowly until 19 April, during spring melt, when an abrupt increase to a sharp peak was indicated by both sensors. The more reliable sensor measured this increase as 4.5 ft (1.37 m) in 10 hours, followed by a 4.3-ft (1.31-m) recession over the next 10 days. These data represent a major flood event in the fen, with rapid onset and efficient drain-out. Such an event has not been observed at any other station in the Flats, and additional investigation is warranted. The Crooked Creek Fen water levels trended upward from mid-May through the end of July 2007, like those at Willow Creek Fen, but with a smaller net increase of 1.0 ft (0.30 m).

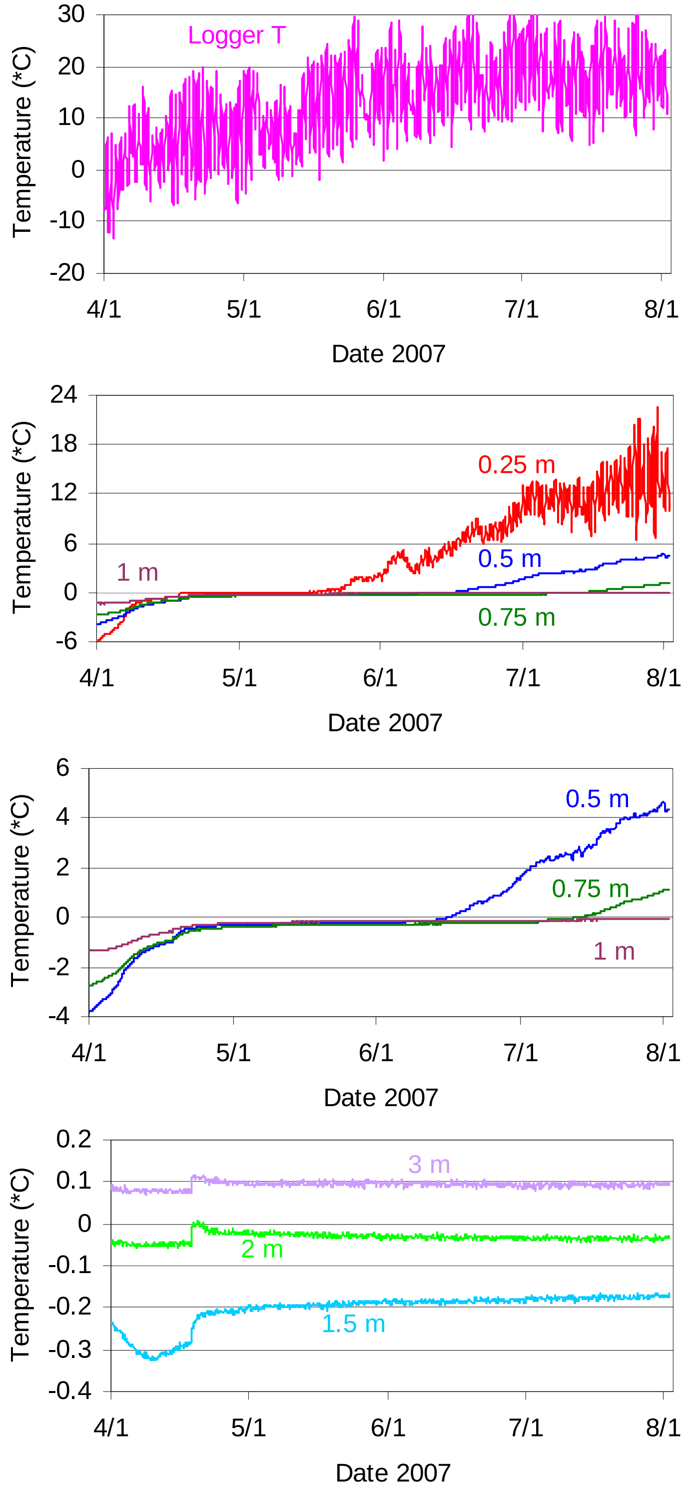

Figure 27. Logger and fen profile temperatures at the Crooked Creek Fen station, April–July 2007.

6 Conclusions

Logger temperature agreement between stations and the Fairbanks airport temperature supports the conclusion that logger temperatures accurately represent local air temperatures. Several general trends emerged from the temperature profiles at the fen stations. Near-surface temperatures are warmer and more variable in summer and colder and more variable in winter than at depth, and these periods are separated by spring and fall overturns of the profile. Large diurnal temperature changes occur during summer at shallow depths, while temperatures at greater depths vary more gradually with features that are lagged in time from those of the shallower sensors. Short-term temperature variability is initiated at the surface, but it decreases significantly at depths of 1 m and greater. Freezing of the various profiles occurred almost every year below 1 m but did not often reach the 2-m depth. These results are consistent with dominant temperature forcing at the surface with only a minor heat flux to the upper 3 m from deeper groundwater. The long record at the Birch Island Fen station indicated an annual temperature variation at the 3-m depth of up to 4.5°C. Winter conditions, including snowpack timing and depth, and air temperature contributed significantly to temperature extremes the following summer. Similarly, the thermal state of the fen during summer was an important contributor to profile temperatures the following winter. Large shifts in the thermal state of the fens have occurred in consecutive years.

Ground temperatures below 0.5 m near the Birch Island well have remained below freezing throughout the year, indicating a locally shallow active layer and stable permafrost, in contrast to many other locations in the Tanana Flats. Most of the losses of permafrost in the Tanana Flats are occurring at fen margins, caused by efficient heat transfer from the warm fen water. However, monitoring of the Birch Island well has provided insight into the less well understood processes that cause melting and degradation on the interior of permafrost islands. Movement of groundwater at temperatures exceeding 1.5°C beneath the permafrost or through fractures and imperfections can supply sufficient heat to cause rapid melting.

Fen water levels follow an annual cycle, with slow recession during the cold late fall and winter months, and fen recharge and water level recovery

with melt in the spring. Water levels in May through October can vary significantly between years, depending on cumulative rainfall in the preceding months. Significant hydrologic deficits that developed in dry years were compensated for in one to two wet months. Data from the station pair of Birch Island Well–Murphy Fen indicated a direct connection throughout the year between water beneath the permafrost and that in the adjacent fen. At high water the fen vegetation is largely submerged, and travel by airboat is easy and without lasting impacts. Conversely, at the lower end of the water level range airboat damage to root mats can be severe and require years for recovery.

Ferrick et al. (2008) reported much larger surface discharge measurements from the Lower Fen than from the Upper Fen. Field observations have inferred a larger inflow of groundwater to the Lower Fen than to the Upper Fen. Also, assuming comparable precipitation on both watersheds, the longer response times at Willow Creek relative to Murphy indicate a much larger basin. As a result of these differences, it is important to manage the airboat access to each fen using local data. Data obtained to date indicate that the full range of Upper Fen water levels exceeds 1.5 ft (0.5 m). Because Murphy station water levels represent a larger part of the Upper Fen than those of the Upper Fen Headwater–Upper Degraded Island station, management of Upper Fen access should be based on measurements at Murphy. The water level range at the Willow Creek Fen station in the Lower Fen was much larger, 3.3 ft (1.0 m). Water levels at Willow Creek represent a sizable fen environment, are related to the nearby surface outflow, and are sustained by a large upstream watershed. As a result, Willow Creek provides the best perspective of any Lower Fen station on water levels for management of access. The minimum water levels for use of each fen should be based on daily web camera readings of the stage gauges installed at Murphy and Willow Creek.

Sustained temperature profile and water level measurements will be important for advancing our understanding of Tanana Flats hydrology in the future. More concurrent data are needed to document the relative responses of headwater, mid-fen, and near-outlet locations. These data help to document the dynamic response of each wetland to water input as well as the movement of water and nutrients through the system. A question remaining to be resolved is whether these fens function like large shallow lakes, wide flat rivers, or a unique wetland system. The flood hydrograph at the Crooked Creek Fen station in April 2007 should be

verified in future years, and the processes causing it should be identified. Surface-driven temperature processes supplement the water level data to better document the seasonal groundwater exchanges. After approaching thermal equilibrium, the annual water temperature response of the groundwater beneath the permafrost at 8 m from the surface should be compared to that at the 3-m depth in the local fen. Also, longer water level records at the Murphy Fen and Willow Creek Fen stations will allow the management of airboat access to be optimized. Ferrick et al. (2008) provided additional study recommendations beyond those associated with the station network.

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14. ABSTRACT
A network of data recording stations has been progressively deployed over recent years in the Tanana Flats to better understand the hydrology of the wetlands and the hydrologic impacts of airboat use. All stations monitor logger temperature, water–soil temperature profiles, and water levels. The logger temperatures at each station accurately represent local air temperatures. Winter conditions contribute significantly to fen temperature extremes the following summer, and conversely, the thermal storage in the fen in the summer is important to temperature conditions the following winter. The water level data provided overall ranges for each fen and indicated a typical annual cycle. Slow recession occurs during the cold late fall and winter months as a result of groundwater outflow, and spring melt is a time of recharge and general water level recovery. Water levels in May through October vary significantly between years, depending on rainfall. Hydrologic deficits that develop in dry years can be eliminated by 1–2 wet months. Conversely, several consecutive large rains can cause high fen water levels. Surface outflows diminish as water levels fall, and moderate levels are sustained by normal rainfall. Data from the station pair at Birch Island Well–Murphy Fen indicate a direct connection throughout the year between water beneath the permafrost and that in the nearby fens. Representative stations in each fen were selected to use for management of airboat access according to local water levels. Staff gauges that can be monitored by web cameras were installed at each of these stations in August 2007. The harsh environment, remote locations, and limited opportunities for access to the stations have often interrupted the continuity of data records. As a result, hydrologic issues remain to be resolved that will require continued station maintenance and operation.

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